S101 Units 26 and 27

THE OPEN UNIVERSITY

Science: A Foundation Course

26 Geological Time

27 Earth Materials and Processes

The Open University

Science: A Foundation Course

Unit 26
Geological time

Prepared by the Science Foundation Course Team

The Open University Press

SCIENCE

S101 Course Team List

A note about the authorship of this text

This text is one of a series that constitutes a component part of the Science Foundation Course. The other components are a series of television and radio programmes, audio-vision materials, home experiments, assignments and a summer school.

The Course has been produced by a team, which accepts responsibility for it.

The Science Foundation Course Team

Mike Pentz (*Chairman and General Editor*)

Francis Aprahamian (*Course Editor*)
David Broadhurst (*Physics*)
Geoff Brown (*Earth Sciences*)
Neil Chalmers (*Biology*)
Bob Cordell (*Biology*)
Glen Davey (*Course Coordinator*)
Graham Farmelo (*Physics*)
Peter Francis (*Earth Sciences*)
Stuart Freake (*Physics*)
Anna Furth (*Biology*)
Denis Gartside (*BBC*)
Charles Harding (*Chemistry*)
Keith Hodgkinson (*Physics*)
Stephen Hurry (*Biology*)
David Jackson (*BBC*)
David Johnson (*Chemistry*)
Tony Jolly (*BBC*)
Roger Jones (*BBC*)
Patricia McCurry (*BBC*)
Perry Morley (*Editor*)
Jane Nelson (*Chemistry*)
Ian Nuttall (*Editor*)
Irene Ridge (*Biology*)
David Roberts (*Chemistry*)
Shelagh Ross (*Course Coordinator*)
Eileen Scanlon (*Research Fellow, Evaluation*)
Milo Shott (*Physics*)
Jacqueline Stewart (*Editor*)
John Stratford (*BBC*)
Steve Swithenby (*Physics*)
Peggy Varley (*Biology*)
Kiki Warr (*Chemistry*)
Barrie Whatley (*BBC*)
Dave Williams (*Earth Sciences*)
Chris Wilson (*Earth Sciences*)

The following people assisted with particular parts or aspects of the Course:

Tel Bailey (*Tutor*)
Mary Bell (*Biology*)
Frances Berrigan (*IET*)
James Brennan (*Biology, Bridgewater State College, USA*)
Joan Brown (*Earth Sciences*)
Beryl Crooks (*IET*)
Linda Fawke (*Tutor*)
Michael Gagan (*Chemistry*)
Ian Gass (*Earth Sciences*)
Ros Hamilton (*Tutor*)
Robin Harding (*Biology*)
Barbara Hodgson (*IET*)
Jen Horgan (*Tutor*)
Graham Jenkins (*Earth Sciences*)
Barrie Jones (*Physics*)
Paul Lyle (*Tutor*)
John Marshall (*Senior Counsellor*)
Bob Maybury (*Chemistry, UNESCO*)
Bob McConnell (*Earth Sciences, Virginia Polytechnic and the State University, USA*)
Laurie Melton (*Librarian*)
Reg Melton (*IET*)
Yow Lam Oh (*Home Experiments, Caulfield Institute of Technology, Australia*)
Robin Russell (*Chemistry*)
Meg Sheffield (*BBC*)
Jane Sheppard (*Designer*)
Jennie Simmons (*Home Experiment Kit Coordinator*)
Peter Smith (*Earth Sciences*)
Russell Stannard (*Physics*)
Charles Turner (*Earth Sciences*)
Arthur Vialls (*BBC*)
John Walters (*Physics*)
Pete Wood (*Home Experiment Kit Coordinator*)
John Wright (*Earth Sciences*)
Martin Wright (*BBC*)

The Open University Press,
Walton Hall, Milton Keynes.

First published 1979 Reprinted 1981, and with corrections 1982

Designed by the Media Development Group of the Open University.

Typeset by Santype International Limited, Salisbury, Wilts, and printed in Great Britain by Eyre & Spottiswoode Ltd., at Grosvenor Press, Portsmouth.

ISBN 0 335 08065 0
This text forms part of an Open University course. The complete list of Units in the Course is printed at the end of this text.

For general availability of supporting material referred to in this text please write to: Open University Educational Enterprises Limited, 12 Cofferidge Close, Stony Stratford, Milton Keynes, MK11 1BY, Great Britain.

Further information on Open University courses may be obtained from the Admissions Office, The Open University, P.O. Box 48, Walton Hall, Milton Keynes, MK7 6AB.

1.3

Contents

TABLE A List of terms and concepts used in Unit 26

Assumed from general knowledge	Introduced in a previous Unit	Unit No.	Introduced or developed in this Unit	Page No.	Introduced or developed in this Unit	Pag No
ammonite	Benioff zone	6/7	absolute dating methods	27	outcrop	19
borehole	crystal	4*	bedding planes (beds)	26	parent isotope	33
chronology	dyke	6/7	biostratigraphic column	26	parent : daughter ratio	33
clay	evolution	20	catastrophism	17	pluton	44
dinosaur	fossils	20	contact metamorphism	43	present is the key to the past	8
erosion	half-life	10/11	correlation	11	primordial lead	42
sand	histogram	HED†	daughter isotope	33	relative dating methods	12
silt	log–linear graphs	21	deluge	17	residence time	31
Stone, Bronze and Iron Ages	meteorite	4	dyke	43	rock-stratigraphic column	26
	palaeontology	20	Eras: Precambrian, Palaeozoic, Mesozoic, Cenozoic	5, 6	sill	43
	radioactive decay processes	10/11	exponential radioactive decay	34	sodium cycle	30
	vesicular lava	4	faunal succession, principle of	19	Stratigraphic Column	6
			geological map	20	stratigraphic sequence	11
			geological Period	6	superposition, principle of	16
			graded bedding	10	unconformity (fossil beach)	19
			Haughton's principle	30	uniformitarianism, principle of	25
			marker horizon	11	tau, τ, half-life of decay process	36
			mega year, Ma (10^6 years)	7	varves	10
					zone, zone fossil	26

* Introduced in the Audio-vision sequence associated with Unit 4, entitled 'The origin of rocks' (AC 90).

† The Open University (1979) S101 *The Handling of Experimental Data* (*HED*), The Open University Press.

Study Guide

You will recall (Units 6 and 7) that events in the fairly recent geological past were said to have happened many tens or hundreds of millions of years ago, while the Earth itself was said to be 4 600 million years old. The main aims of this Unit are to explain how geological events can be sorted out and arranged in the order in which they occurred, and how they can be dated. Dating methods vary from simple observations made in the last century to the much more accurate quantitative methods of today, based on naturally occurring radioactive isotopes. You will see as you follow the development of dating methods through the Unit how ideas about the age of the Earth have evolved from early uncertain estimates to the present seemingly accurate figure of 4 600 million years.

Once you understand how rocks can be dated, you will be in a better position to study rock-forming processes (Unit 27) and the history of the Earth (Unit 28).

The TV programmes for Units 26–28 are not tied to the individual main texts but illustrate principles discussed in all three Units by showing geologists in the field. The first two show rock-forming processes on the surface of the Earth (TV 26) and inside the Earth (TV 27), whereas TV 28 shows two geologists working in the Isle of Arran. The radio programme (R13) shows how city-dwellers can see many rocks of geological interest in the High Street. There are two filmstrips associated with this programme, 26.1 and 26.2.

There is a Home Experiment, which you should do after this Unit and before you begin to study Unit 27, concerned with the rate at which particles settle through water. (The *Home Experiment Notes* for this are printed separately.) Unit 26 has been kept somewhat shorter than others to allow you time to do this experiment this week.

1 Introduction to geological time

Study comment This short Section introduces the enormous scale of geological time and shows how it has been divided into four major Eras, each made up of shorter Periods. At the end of this Section you should understand how the ages of your Home Experiment Kit rock specimens relate to their positions in the Stratigraphic Column. Get your Home Experiment Kit samples out before you start.

From Units 4–7 you already know that all rocks in the Earth can be divided into three major groups: igneous, sedimentary and metamorphic. In the next three Units you are going to learn more about rocks themselves and rock-forming processes. First of all, try some revision ITQs with your Home Experiment Kit rock samples:

ITQ 1 Arrange the specimens in three rows:

(a) Igneous

(b) Sedimentary

(c) Metamorphic. (Metamorphic rocks are rocks that were originally sedimentary or igneous rocks that have been altered by being exposed to high temperature and pressure. They are discussed in more detail in Unit 27 and its associated Audio-vision sequence. For the purpose of this ITQ, assume that any rock that you cannot readily identify as igneous or sedimentary is metamorphic.)

Answers to ITQs begin on p. 48.

Make sure you have the correct answers before you go on.

You also learnt in Unit 4 about the density of some of your Home Kit samples.

ITQ 2 Taking the whole specimen:

(a) Which is the least dense rock, and *why*?

(b) Which is the densest rock, and *why*?

(c) Is there likely to be a large difference in density between the granite (S1) and the gneiss (S10)?

In Unit 27 you will learn much more about the chemical composition of these rocks, their texture, mineralogy, where they were formed, and their relationship to the Earth's crust and mantle.

What other basic data are missing? How old are they? So far, there has been no mention of how we know the age of rocks—just how old *is* each of your specimens, do you suppose?

The granite (S1) is nearly 400 million years old, the solid basalt (S3) 60 million years, and the vesicular basalt (S2) a geological stripling at a mere 10 million years! But how do we know this? Is it likely to be by studying the minerals present, or their chemical composition?

No, the *relative* ages of different rocks which are found exposed near to each other at the Earth's surface can be worked out from the relationships between them as they occur in the field. Geologists can also calculate 'real' ages using the radioactive isotopes present in some rocks, especially in igneous rocks, such as your samples S1 to S5.

The following summary of the stages of the Earth's history has been drawn up from geological time studies over the past two hundred years. The rest of this Unit will show how this chronology was worked out.

The whole of geological time is divided into four major divisons called *Eras* (see Table 1). These Eras were defined and given their names from the general character of their fossils long before geologists knew anything about the timescales involved, at a time when the beginning of the Palaeozoic was thought to correspond roughly to the origin of life. (You will see how far this is from the truth in Unit 28.) **Era**

TABLE 1 The geological Eras

Era	Meaning of name	Timespan
Cenozoic	(recent life)	present to 65 million years ago
Mesozoic	(middle life)	65 to 225 million years ago
Palaeozoic	(ancient life)	225 to 570 million years ago
Precambrian	(before the Cambrian)	older than 570 million years

Stratigraphic Column

These Eras have been arranged with the *oldest at the bottom* here and in Figure 1 to form the *Stratigraphic Column* for the Earth. The Stratigraphic Column is made by stacking up the rocks formed during each geological Era in their correct sequence, always starting with the oldest at the bottom.

It is important that you should remember the names and approximate dates of the four Eras, since they are in common use in any discussion of geological time.

Period

As you can see from Figure 1, the last 570 million years is further subdivided into eleven *Periods*. These again, as you will see in Section 3, were defined long before any radiometric ages were known.

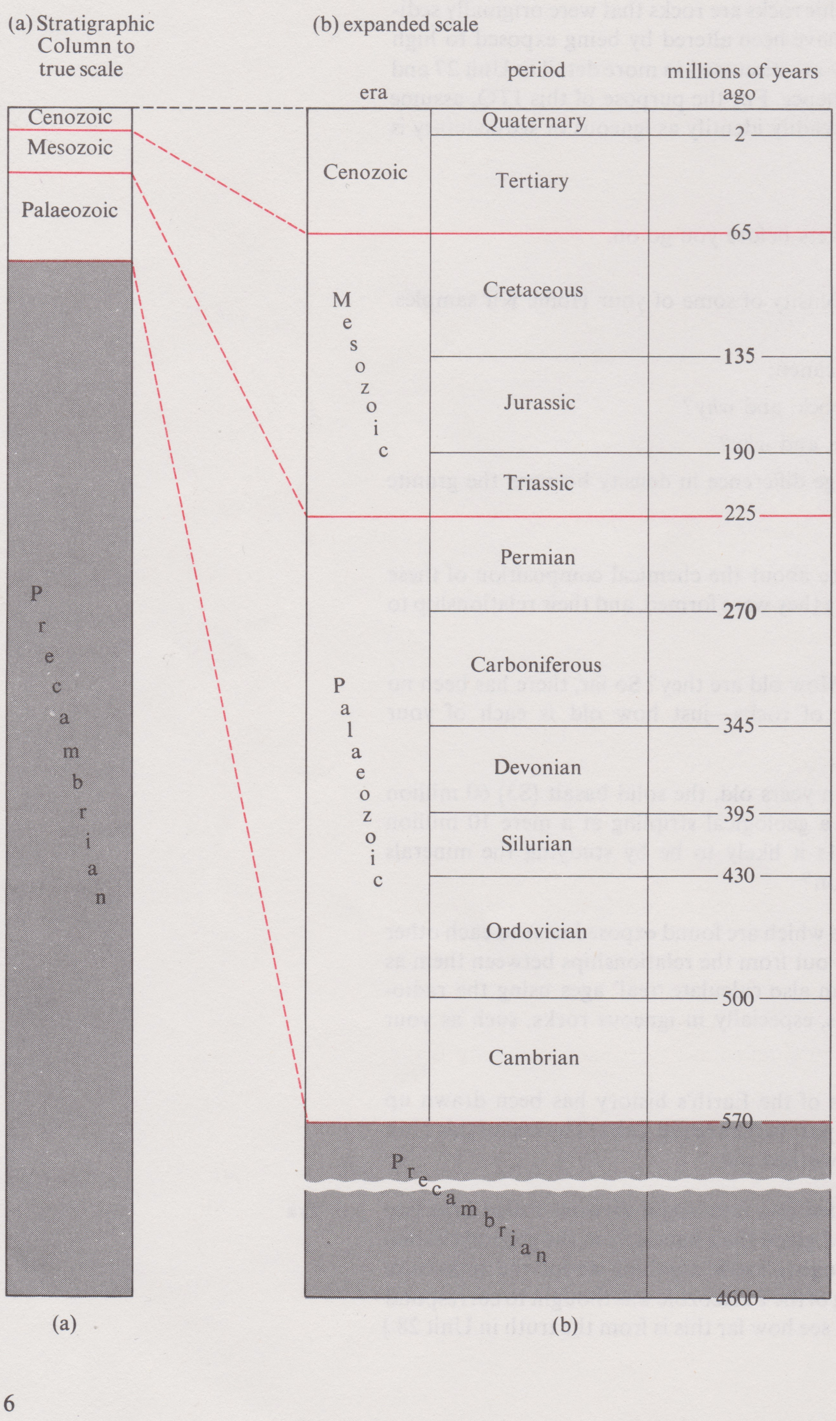


FIGURE 1 Stratigraphic Column for the whole of geological time. (a) To true scale: note the length of the Precambrian Era, about 4000 million years, or nearly 90 per cent of geological time. (b) Expanded scale since the Cambrian, to show details of the Periods in the three most recent Eras: Palaeozoic ('ancient life') Mesozoic ('middle life') and Cenozoic ('recent life').

The ages and localities of the rocks in your Home Experiment Kit are given in Table 2, from which you will see that you have representatives from the three most recent Eras.

TABLE 2 Ages and localities of Home Experiment Kit rock specimens

No.	Rock	Locality	Age / Ma	No.	Rock	Locality	Age / Ma
S1	granite	Peterhead, Aberdeenshire	385	S6	sandstone	Leeds, England	300
				S7	limestone	Derbyshire, England	320
S2	vesicular basalt	Auvergne, France	10	S8	phyllite	Kinlochleven, Scotland	400
S3	effusive basalt	Skye, Scotland	60	S9	schist	Loch Ness, Scotland	450
S4	peridotite	Ivrea, Italy	70				
S5	gabbro	Aberdeenshire, Scotland	430	S10	gneiss	Ivrea, Italy	70

When you have completed this Unit you should understand the methods that can be used to show that, for example, your sandstone sample, S6, was formed about 300 million years ago and belongs to the Carboniferous Period of the Palaeozoic Era.

You may remember from Unit 2 (Section 1.3) that the natural unit of time, the second, is now defined in terms of the number of vibrations of caesium atoms in the 'atomic clock'. These atomic processes are extremely fast—each vibration taking only 1.088×10^{-10} seconds. You have also met very slow processes: for example visible changes due to evolution may take years to appear (Unit 20); while the rate of sea-floor spreading, although measured in only centimetres per year, can cause oceans to form over a timespan of tens to hundreds of millions of years (Units 6 and 7).

ITQ 3 (a) Calculate the length of the human lifespan (70 years) in seconds.

(b) In Units 6 and 7 you learnt that the world's ocean basins were created in about 100 million years. How many human lifespans is that?

(c) How many human lifespans old is the Earth itself?

This Course uses SI units wherever possible, but the unit of time for a million years, namely the *mega year* (*Ma*), is most convenient for geology, so a rock formed 200 million years ago would be dated as 200 Ma.

mega year, Ma

1.1 Objectives of Section 1

Now that you have finished this Section, you should be able to appreciate the enormous scale of geological time and achieve the following:

(a) Perform simple calculations involving time over many orders of magnitude. (SAQ 1)

(b) Define the terms Era and Period, recall the four major Eras of geological time, and from given data on the Stratigraphic Column assign a rock of given age to its correct Period. (SAQ 2)

Now test your achievement of these objectives by attempting the following SAQs.

SAQ 1 (a) The age of the Earth is 4 600 Ma and man has been present here for about 3 Ma. Suppose that the age of the Earth is equivalent to a 3-hour film, how long before the end of the film did man appear?

(b) If the history of civilization is taken as 5 000 years, how long is that before the end of the film?

SAQ answers begin on p. 54.

SAQ 2 (a) From the information in Table 2, assign each rock specimen in your Home Experiment Kit to its correct Era in the Stratigraphic Column.

(b) From the information in Table 2 and Figure 1, assign each rock specimen in your Home Experiment Kit to its correct Period in the Stratigraphic Column.

2 Ordering events in time

Study comment This Section is concerned with the ways in which past events can be ordered by observation and interpretation. The crucial principle here is that by studying present-day sequences in natural processes it is possible to work out similar sequences in the past. This Section considers just a few examples, starting with the very recent past.

2.1 Key to the past

Even before people had any accurate means of measuring time they knew that there were regular sequences in nature: day follows night, spring follows winter, and sometimes the results of these daily or annual fluctuations are preserved in nature, for example, in annual tree rings.

From what is known of the forces controlling the processes that can now be observed on the Earth's surface, namely the laws of physics and chemistry, there is no evidence that they were any different in the past. It seems reasonable, therefore, to suppose that the *present is the key to the past*. This commonsense approach to the interpretation of past geological events may seem very obvious today, but it was a revolutionary idea when it was first presented about 150 years ago, as you will see in Section 3.

present is the key to the past

There is one further implication of the principle that the present is the key to the past: it can also be used in some cases as a key to the future. Some geological events happen on a timescale that makes their prediction of vital importance to us, earthquakes and volcanoes being the most dramatic examples. In many countries well away from plate boundaries, including Britain, there is little chance of major damage by either of these in the foreseeable future, but on a slightly longer timescale it is important to know whether a new Ice Age is imminent, a problem which is discussed again in Unit 28.

Occasionally, it is possible to work out a chronology giving actual dates, by counting annual events of the fairly recent past, starting from the present and working back. But, apart from radioactive dating (Section 5), most geological methods are purely relative: they can only be used to work out the *relative* order in which things happened.

2.2 Putting things in order

The ways in which geological events can be ordered in time can best be explained by example and analogy.

Consider first an example from the recent past. Various objects have been found in old refuse dumps near mining camps in North America, and seven examples of these are shown in Figure 2. Their distribution in three boreholes through one dump is shown in Figure 3. The dates of manufacture of the bottles, cans and nails are known from their makers' old records, and so a 'range chart' can be worked out showing the duration of manufacture of each item (Figure 2). You will realize that some of these articles can be used to give a fairly exact age to a part of the dump because they were in use for only a few years, while others were used over a long time and so are not so valuable for dating. Some groups of articles were only in use together for a very short time, and so an assemblage of these found together can tie down the age of the dump very precisely. (For example, finding items 3 and 4 together would indicate the date of 1900.) Now try ITQ 4.

ITQ 4 With the aid of the 'range chart' in Figure 2, work out the ages of the rubbish in boreholes A, B and C in Figure 3.

In a directly analogous way many sedimentary rocks can be dated by the fossils they contain. You have already met the fossil remains of early man in Unit 20, where fragments of bone have been preserved in geologically recent river gravels, little altered apart from staining by mineral salts from percolating waters. *Fossils* can be formed when plant or animal remains become buried in accumulating

fossils

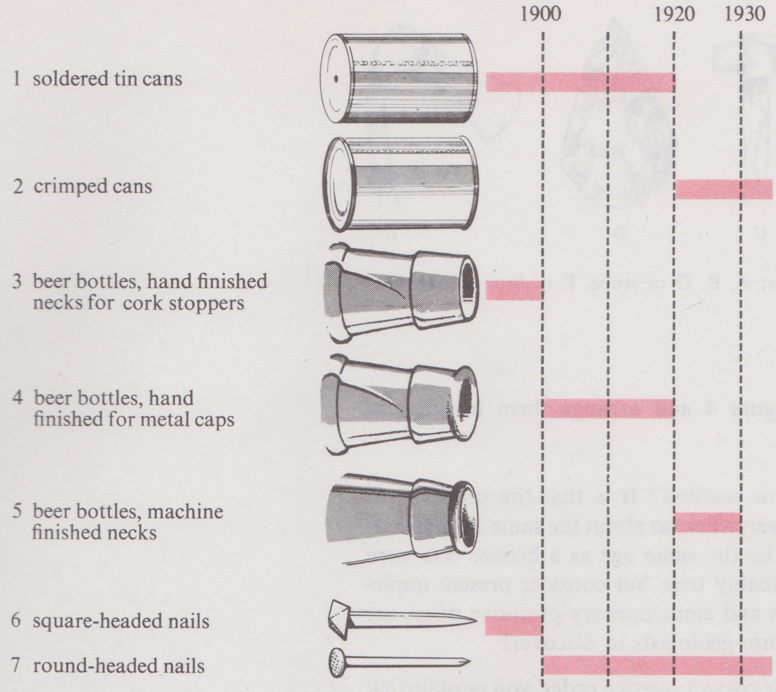


FIGURE 2 Range chart of dates of manufacture of cans, bottles, and nails prepared from historical records. Each articles is given a number, and these numbers are used in Figure 3 to show where the articles were found in the boreholes.

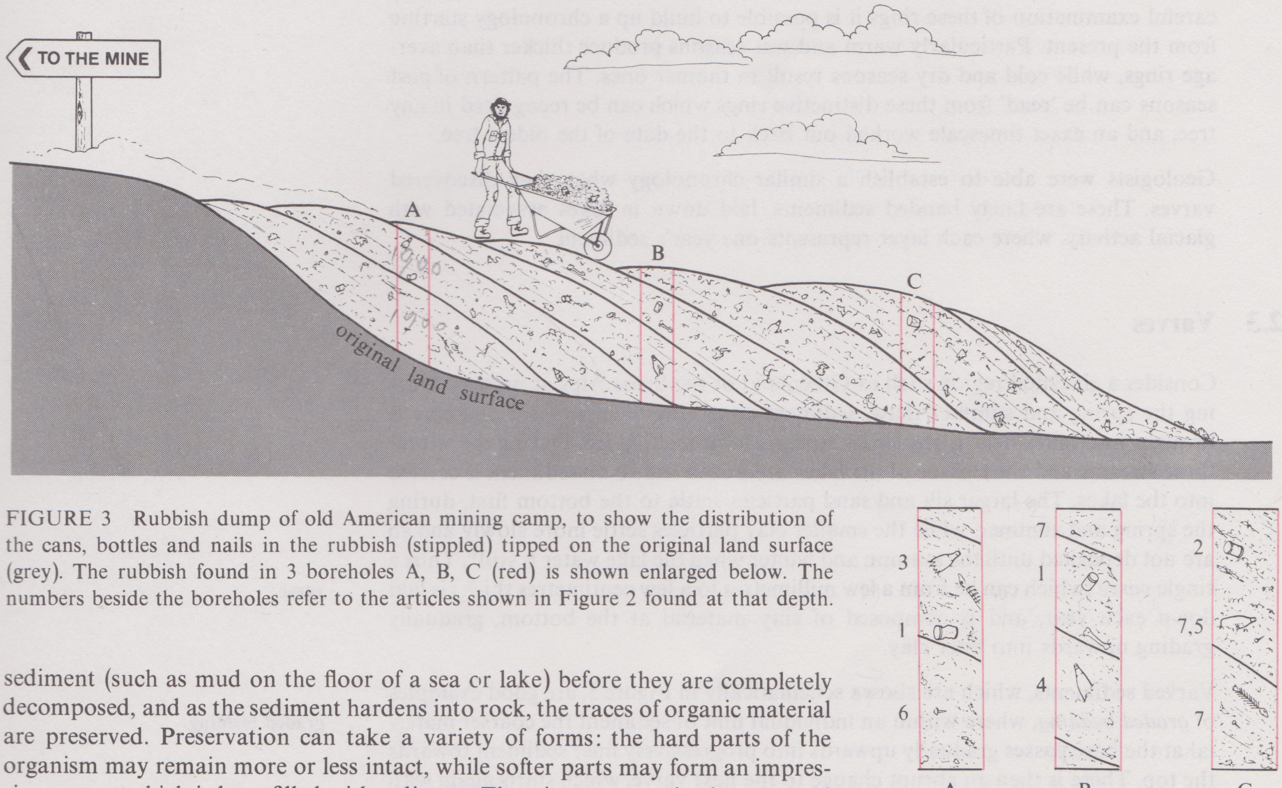


FIGURE 3 Rubbish dump of old American mining camp, to show the distribution of the cans, bottles and nails in the rubbish (stippled) tipped on the original land surface (grey). The rubbish found in 3 boreholes A, B, C (red) is shown enlarged below. The numbers beside the boreholes refer to the articles shown in Figure 2 found at that depth.

sediment (such as mud on the floor of a sea or lake) before they are completely decomposed, and as the sediment hardens into rock, the traces of organic material are preserved. Preservation can take a variety of forms: the hard parts of the organism may remain more or less intact, while softer parts may form an impression or cast which is later filled with sediment. Thus, insects completely preserved in every detail in drops of amber (fossilized resin) and the footprints left by a dinosaur on an old land surface can both be described as 'fossils'.

The next example goes back a little further in time to consider the tools of our early ancestors, and the ways in which these tools were modified and improved as time went by. From Unit 20 you will recall that man appeared on the Earth about 3 Ma ago, and Figure 4 illustrates some of the primitive tools he invented. These tools can be used to date early remains since the sequence in which they were developed is now known, through first the Stone Age, to Bronze Age and then Iron Age.

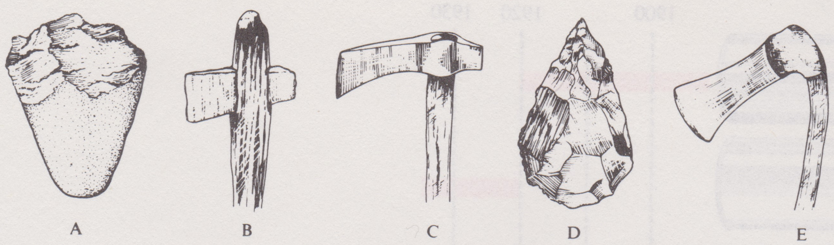


FIGURE 4 Axes made of various materials: A, B, D of stone, E of bronze, and C of iron (for use with ITQ 5).

ITQ 5 Examine the axes in Figure 4 and arrange them in order of decreasing age.

Can you see the assumption behind this method? It is that the use of tools 'evolved' from Stone to Bronze to Iron everywhere at about the same time (otherwise a stone axe from one area might be the same age as a bronze one from elsewhere). On a broad scale this is probably true, but consider present implements: people in industrialized countries and contemporary primitive tribes are producing very different artefacts for future geologists to discover!

Once you have placed these items in their correct relative order, you need further information to find out when the tools were used, that is, some quantitative method of measuring time is needed.

You may have seen the rings in a cut tree-stump, and you probably know that you can find the age of the tree by counting these annual rings. The oldest living trees are bristlecone pines in California, which have up to 4900 annual rings! By careful examination of these rings it is possible to build up a chronology starting from the present. Particularly warm and wet seasons produce thicker than average rings, while cold and dry seasons result in thinner ones. The pattern of past seasons can be 'read' from these distinctive rings which can be recognized in any tree, and an exact timescale worked out back to the date of the oldest tree.

Geologists were able to establish a similar chronology when they discovered varves. These are finely banded sediments, laid down in lakes associated with glacial activity, where each layer represents one year's sediment.

2.3 Varves

Consider a glaciated region such as Greenland or the Swiss Alps at present. During the spring and summer thaw, sediment consisting chiefly of silt and clay is brought into lakes near a glacier by streams from melting ice. During the winter these streams and the surface of the lakes are frozen and so no sediment is carried into the lakes. The larger silt and sand particles settle to the bottom first, during the spring and summer, while the smaller clay particles settle more slowly and so are not deposited until the autumn and winter when the lake water is still*. Thus a single *varve* (which can be from a few millimetres to a few centimetres thick) is laid down each year, and is composed of silty material at the bottom, gradually grading upwards into finer clay.

varve

Varved sediments, which are shown schematically in Figure 5, are good examples of *graded bedding*, where within an individual unit of sediment the coarser material at the base passes gradually upwards into progressively finer sediment towards the top. There is then an abrupt change to the next varve, which starts again with coarser-grained material brought down by the rush of waters produced by melting the following spring.

graded bedding

Varved sediments are useful to geologists trying to work out details of the past because a few years result in distinctive layers: a particularly hot summer will give

* The relationship between the size of a sedimentary particle and the speed with which it falls through water is very important in sedimentary rock formation and you will investigate this in the Home Experiment for this Unit. This experiment prepares the way for a more detailed study of sediments in Unit 27.

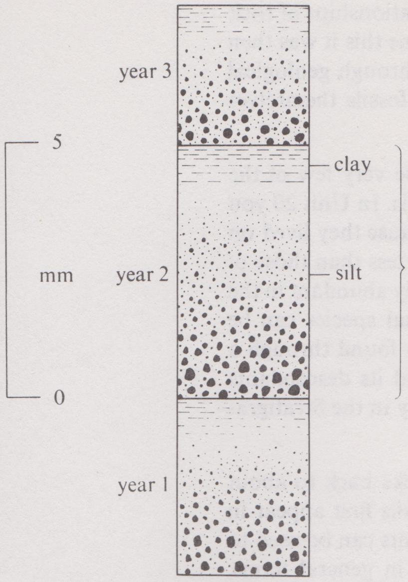


FIGURE 5 Vertical sequence of varves, in which each individual layer represents one year's sediment. This is an example of graded bedding, where there is a *gradual* change upwards from coarser to finer sediment within each annual layer, in contrast to the abrupt change from fine to coarse at the base of each layer.

more sediment as more ice is melted, and so produce a thick varve; conversely thin varves result from cool, dry summers. By studying the pattern of varves in deposits from many different lakes the sediment of distinctive seasons can be recognized in several different places, thus enabling geologists to correlate the sediments. *Correlation* is the recognition of some past event in the sedimentary record in more than one place, enabling the adjacent sediments to be shown to be of the same age. In the cases of bristlecone pines and varves, short periods of time are correlated by matching records of particularly unusual seasons. A distinctive bed which is useful in correlation from lake to lake, is called a *marker horizon.*

correlation

marker horizon

Varves formed during the Quaternary Period are best developed in Scandinavia and eastern North America, and the longest chronology has been worked out in Sweden and Finland, dating events through about the last 12 000 years and correlating the varves from sites as far as 1 000 km apart. To make use of this method, one has in some way to *date* one of the varves, and the best way to do this is to find a lake where varves are still being formed and then to start from this year's varve and count backwards.

Although geologists normally have to work with strata where individual units do not represent annual events, the principle of finding distinctive marker horizons which can be correlated from one place to another is exactly the same. Then, having established the sequence of strata in an area, another method such as radiometric age determination is needed to establish an *actual* age. Varves are interesting but as they are clearly limited to thousands of years, they are of little use to geologists, most of whom work on a timescale many orders of magnitude greater. Ideally, we want a chronology that goes back to the beginning of the Earth, thousands of millions of years ago.

2.4 Evolution

Fossils are now widely used to determine the relative ages of rocks, and so place them in their correct order, that is, their correct *stratigraphic sequence*. But how was this sequence originally worked out? As you will see in Section 3.3, William Smith and Georges Cuvier discovered that overall there is a sequential order of fossils through time; the biological explanation of this came later, particularly with the work on evolution by Charles Darwin (1809–1882).

stratigraphic sequence

You will recall from Unit 20 that much of the general course of evolution can be verified by the study of fossils. By careful collection palaeontologists have discovered a discontinuous record of fossils in the Stratigraphic Column from the end of the Precambrian to the present. The stratigraphic sequence of the rocks was

established first by mapping them in the field and, from the relationships of rock strata to each other, deciding on their relative ages. Having done this it was then possible to work out the sequence in which fossils appeared through geological time. Once this sequence of fossils had been established, the fossils themselves could then be used to date other rocks.

The fossil record is not complete, as you can imagine, because very few of the animals and plants living at any one time are preserved as fossils. In Unit 20 you saw how few specimens of hominids have been discovered. Because they lived on land, their chances of being preserved in sediments were much less than those of animals that lived in the ocean. Some marine organisms are fairly abundant in the rocks in which they are found and the evolution of individual species can be traced in greater detail. Sometimes a particular species is only found through a few metres of rock in one Period, with its ancestors below, and its descendants above. In such cases a single fossil can pinpoint very accurately in the Stratigraphic Column the rock in which it is found.

Fossils can now be used to determine the relative ages of rocks back to about 600 Ma before the present, at which time abundant shelly fossils first appear in sedimentary rocks. The evolutionary order of animals and plants can be used to establish the relative ages of rocks because we assume that, in general terms, evolution proceeds from simpler to more complex organisms; for example, the evolution of the vertebrates followed the sequence:

fish $\longrightarrow$ amphibia $\longrightarrow$ reptiles $\longrightarrow$ mammals.

If we place this sequence in stratigraphic order we have:

youngest beds	fish	amphibia	reptiles	mammals (150 Ma)
	fish	amphibia	reptiles (300 Ma)	
	fish	amphibia (350 Ma)		
oldest beds	fish (400 Ma)			

Before the Devonian Period the only vertebrates were fishes; by about the Cretaceous all four groups had evolved.

Thus the oldest rocks in this sequence will contain only fossil fish and the youngest, besides containing mammals, will also yield fossils of all four groups which have evolved from the common ancestor, the fishes. The detailed evolution of the vertebrates, to which all these animals belong, is much more complicated than this (Figure 6). For example, during the Jurassic and Cretaceous Periods (the age of the dinosaurs) fish, amphibia, dinosaurs and reptiles existed, but mammals and birds were barely significant.

When the relative ages of strata from different localities have been established by the sequence of the fossils they contain, the rocks can be arranged into a Stratigraphic Column, but no actual ages can be given to rocks by the use of fossils alone; it is therefore only a *relative dating method*.

relative dating method

Before returning to see how the ideas of the Stratigraphic Column were worked out, consider how you could attack a similar problem, of working out the order of events on the Moon, knowing that few of the techniques used on Earth can be applied to such a remote body. Certainly, despite imaginative hopes to the contrary, no evidence for past life has been detected in lunar rocks.

FIGURE 6 Geological range of the vertebrates to show when the various groups of animals evolved from each other. The width of each group indicates the approximate number of species living at that time.

2.5 Craters on the Moon

When NASA geologists began to work out the relative ages of events on the Moon before the first Apollo landings, all they had to work with was pictures of the lunar surface similar to the general view shown in Figure 7 and close-up photographs such as Figure 8.

It has been known for a very long time that the Moon's surface was pock-marked with circular craters, which had been formed by impacts of meteorites with high velocities. These impacts cause the metorite material to fragment and vaporize, making features in the dust and rocks of the Moon's surface much like those which you could make by dropping marbles into stiff mud. Material of the lunar surface is ejected to form a rim around the impact crater, and sometimes rays of material radiating outwards from the crater.

> The Moon's surface is very old compared with the Earth's. Can you think why this should be so, bearing in mind what you learnt in Units 6 and 7 about the Earth's surface?

FIGURE 7 General view of the visible face of the Moon showing abundant craters especially in the lighter areas.

FIGURE 8 Close-up oblique view of part of the Moon's surface (for use with ITQ 6).

Because the Earth's surface is being constantly reworked by weathering, erosion, deposition, and by sea-floor spreading, none of which occur on the Moon.

On a planetary body without these processes, can you see how craters can be used to work out the relative ages of different parts of the lunar surface?

Craters can be compared to footprints after high tide on a holiday beach: the longer the sand is exposed the more prints can be formed. Meteorites come in a variety of sizes, and they impinge randomly on the Moon's surface. So if craters of a particular size are compared in two areas, the more densely cratered must have been exposed for a longer time.

ITQ 6 Look at Figure 8. Is the lighter material in the centre of the picture (just to the right of the large crater) older or younger than the darker surface below it and to the right, along the bottom of the photograph?

2.6 Objective of Section 2

In this Section you have learned about some of the way in which relative time-scales can be established, and you should now be able to achieve the following:

(a) Be able to apply the principle that the present is the key to the past, by placing given natural events in their correct chronological order. For example you should be able to interpret a sequence of varved sediments. (SAQs 3 and 4)

Now test your achievement of this Objective by attempting the following SAQs.

SAQ 3 Explain how graded bedding in varved sediments can be used to interpret varves as annual layers of sediment deposited in glacial lakes which become frozen over each winter.

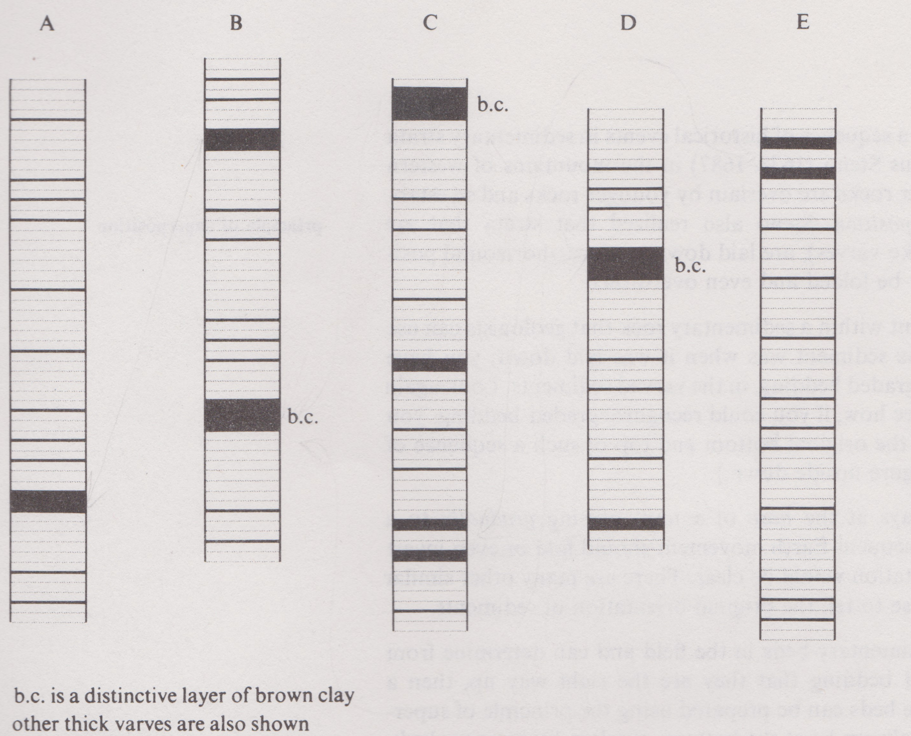


FIGURE 9 For use with SAQ 4. Measured sections of varved clays from five glacial lakes. Each black line represents the coarse fraction of one year's sediment laid down in the summer, the white layer above being the finer sediment laid down during the winter. A few exceptional years are represented by very thick black beds, where an abundance of organic material colours the whole year's sediment. (These years have no white layer on the diagram.) The thickest layer of all (labelled b.c.) forms a distinctive marker horizon, containing abundant brown clay.

SAQ 4 Figure 9 shows a series of measured sections of varved sediments in boreholes from different glacial lakes. Each black line in the diagram represents the coarse fraction of a year's sediment (the layer of silt), the white layer above being the fine sediment deposited in the winter. In many years, due to a longer summer season, a thicker layer of coarse sediment was laid down. Several exceptional seasons are characterized by an abundance of organic material and are shown as black layers more than 1 mm thick. (These years have no white layer in the diagram.) One such layer (labelled b.c.) contains distinctive, brown, lake clay and appears in several of these sections, thus providing a useful marker horizon.

(i) Correlate these sections by matching the distinctive beds.

(ii) Draw up your own stratigraphic column for this sequence of beds.

(iii) In which borehole are the oldest beds?

(iv) How many years are represented by this stratigraphic column?

3 How the Stratigraphic Column was developed

Study comment This Section describes some of the key discoveries, mostly made in the nineteenth century, that enabled the Stratigraphic Column for the Earth to be worked out. From the principles of superposition of rock strata (oldest beds at the bottom), faunal succession (the regular sequence of fossils with time), and uniformitarianism (the present is the key to the past), combined with mapping of rocks in the field, arose a picture of a gradually evolving Earth, which was in contrast to the earlier catastrophic theories of Earth history. All this was long before any actual dates could be assigned to past geological events. This Section is concerned entirely with working out *relative* ages, and is fairly straightforward. Early attempts to work out actual dates are considered in Section 4.

3.1 Superposition

The first attempt to recognize a sequence of historical events in sedimentary strata was made by a Dane, Nicolaus Steno (1638–1687) in the mountains of western Italy. He recognized that older rocks are overlain by younger rocks and so established the *principle of superposition.* Steno also realized that strata that are normally deposited slowly (like varves), are laid down in a near-horizontal position, although later they may be folded and even overturned.

principle of superposition

There are often features present within a sedimentary rock that geologists can use to interpret which way up the sediment was when it was laid down; you have already met one such feature, graded bedding, in the varved sediments. Look again at Figure 5 (p. 11). Can you see how, if you could recognize graded bedding, you would always be able to tell the original bottom and top of such a sequence of strata? (Try looking at the figure upside down.)

The coarser material is always at the *base* of a unit, passing *gradually* to a finer-grained top. Even if subsequent Earth movement should fold or even invert these rocks, the original orientation would be clear. There are many other similar features that geologists can use to tell the original orientation of sediments.

If we examine a series of sedimentary beds in the field and can determine from some feature such as graded bedding that they are the right way up, then a stratigraphic column for these beds can be prepared using the principle of superposition: the oldest beds will always be at the bottom, overlain by younger beds. You can see this clearly in Figure 3 (p. 9), with the 'beds' of the mine dump. Younger rubbish overlies old rubbish, although the 'beds' here were not laid down exactly horizontally!

3.2 First attempt at a Stratigraphic Column

An Italian, Giovanni Arduino (1713–1795), prepared a simple stratigraphic column for the rocks of northern Italy. Having studied how individual rock strata were related to each other where he saw them exposed in the field, and having looked at the character of the rocks themselves, he split his column into three:

Tertiary soft limestone with fossils, clays and sandstones;
Secondary hard limestones and mudstones with fossils;
Primary severely folded metamorphic and igneous rocks without fossils.

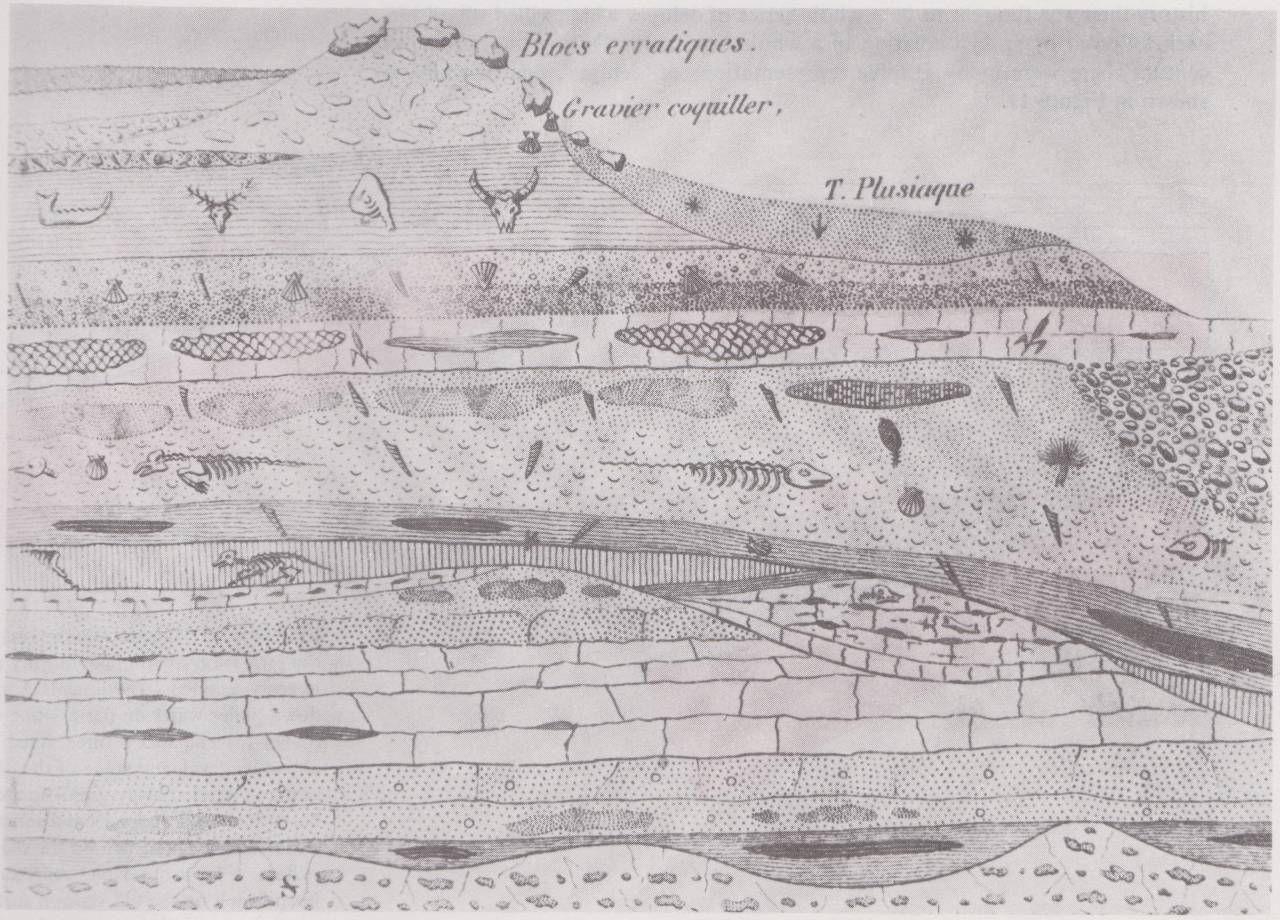
If you examine the modern Stratigraphic Column (Figure 1), only the term 'Tertiary' has survived from this first classification (as a Period name within the Cenozoic). Arduino's 'Secondary' very roughly corresponds to the present Mesozoic and Palaeozoic Eras combined, and his 'Primary' is roughly equivalent to the present 'Precambrian' Era. This was a beginning, but there was no certainty that these three divisions could be applied elsewhere, because there were no clearly expressed criteria to separate them, particularly the upper two divisions. There was no reason to suppose that rocks of similar age elsewhere would look the same as these strata in Italy.

3.3 Faunal succession

Early philosophers, such as the Greek, Herodotus, deduced accurately in the 4th century B.C. that fossils, representatives of ancient life forms now preserved in rocks, were the remains of ancient sea creatures. He believed that this indicated that the rocks in which they were found had been formed originally beneath the sea. However, this theory, along with many other perceptive theories of the ancient Greeks, became lost during the next 2 000 years, overshadowed by religious beliefs. Even as late as the seventeenth century in Britain, some scholars thought that the Earth was only 6 000 years old. The most plausible explanation offered for fossils was that they were either relics of Noah's Flood, or the work of the Devil, who deliberately placed fossils in rocks to 'deceive, mislead and perplex mankind'.

A Frenchman, Georges Cuvier (1769–1832) was one of the first to describe systematically the skeletal remains found preserved in rocks as fossils, to interpret them in terms of the living organisms they represented, and to work out their succession in Earth history. He studied the fossil plants and animals in the Tertiary rocks of the Paris Basin, and concluded that older fossils differed more from living creatures than did younger ones. He summarized his conclusions diagrammatically by sequences of strata, such as those shown in Figure 10. He deduced from these that some older forms of life had become extinct and that the extinct forms had been replaced by newer forms.

FIGURE 10 Diagrammatic section of strata (after Cuvier), showing how particular fossils are associated with particular horizons in the sequence of strata. Breaks in the sequence where erosion of the underlying beds has occurred before subsequent beds were laid down can be seen in several places, perhaps best where strata with a walking vertebrate (shown by vertical ruling) are overlain by a horizontally shaded bed.



But some of Cuvier's conclusions were not correct. For example, in his answer to the question of how new species arose, Cuvier believed that each old species was wiped out by a universal catastrophe followed by the 'special creation' of new species.

catastrophism

deluge

Catastrophism is the name given to the idea that geological history can be explained by a series of catastrophic events. Starting from the biblical idea of the Flood, Cuvier invoked similar 'deluges' to explain each break in the series of fossils in his sequence of sediments. Since he was not able to find intermediate species connecting the fossils at different levels in the Stratigraphic Column, and since, moreover, there was often evidence of a break in the deposition of the

FIGURE 11 The Asiatic Deluge, from Louis Figuier (1869) *The World before the Deluge.*

sediments themselves, marked by changes in rock type that coincided with the faunal changes, it was logical to invoke a new 'deluge' for each break. Geological history then was thought to be a whole series of deluges which killed off all life, each followed by special creation of a whole new fauna. During the nineteenth century there were many graphic representations of 'deluges', one of which is shown in Figure 11.

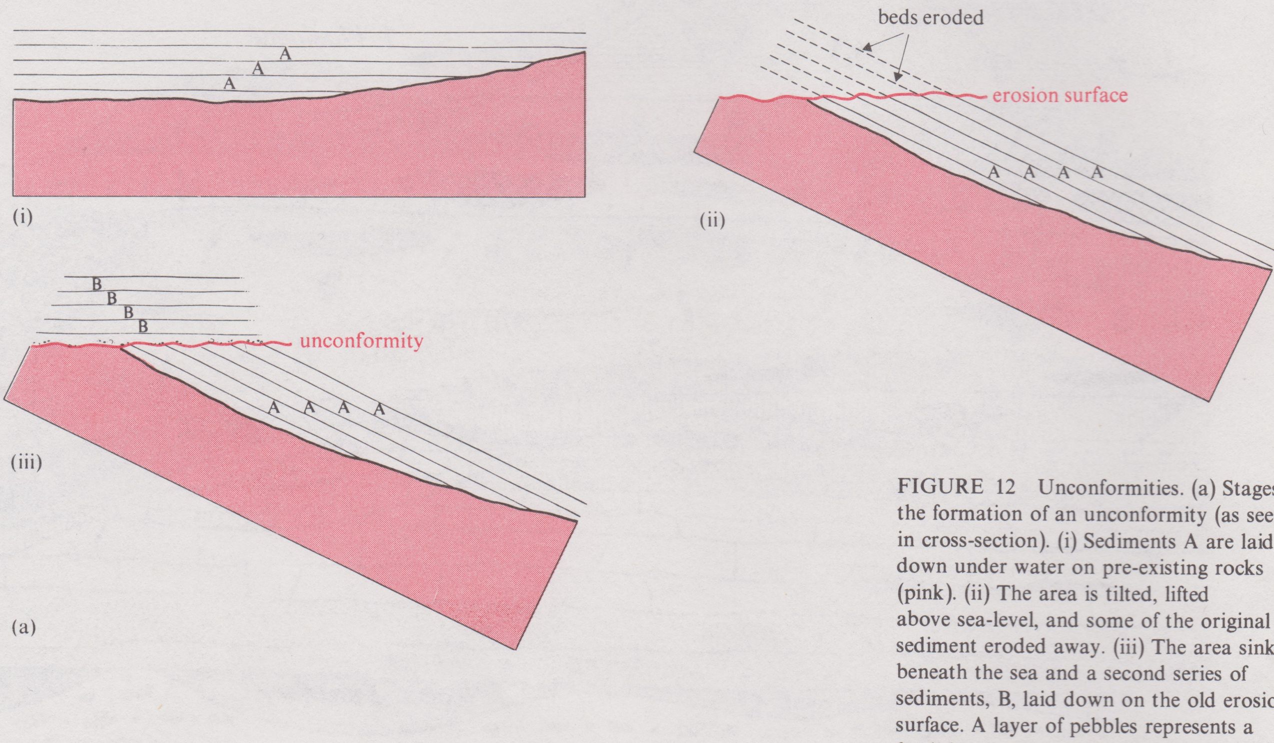
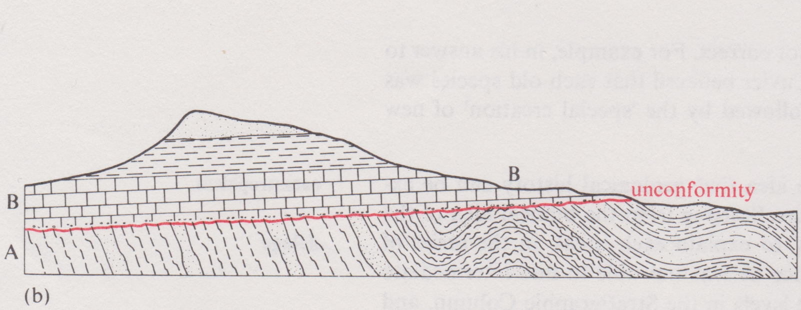


FIGURE 12 Unconformities. (a) Stages in the formation of an unconformity (as seen in cross-section). (i) Sediments A are laid down under water on pre-existing rocks (pink). (ii) The area is tilted, lifted above sea-level, and some of the original sediment eroded away. (iii) The area sinks beneath the sea and a second series of sediments, B, laid down on the old erosion surface. A layer of pebbles represents a fossil beach on the old erosion surface, which is now called an unconformity.
(b) Cross-section of a typical unconformity (simplified) which occurs in the Ingleton area. The time interval represented by the unconformity can be many tens or hundreds of Ma. In this case the older strata, A, were folded and eroded before the younger strata B were laid down. Since strata B were deposited there has only been slight tilting and uplift, and erosion to form the present land surface.



Cuvier noticed that very often the breaks in the sequences of strata and fossils were marked by a horizon where there was evidence of erosion of the underlying beds before deposition of the next layer, and that the beds immediately above contained pebbles. Indeed this was powerful evidence for the 'deluge'. Such breaks in the Stratigraphic Column often do represent a long interval of time, during which sedimentation ceased and erosion occurred because the area had risen above sea-level. They are important features of the Stratigraphic Column, and are known as *unconformities*. Several unconformities are shown in Figure 10. The stages in the formation of an unconformity are shown in Figure 12. The pebble bed that marks the time when the area sank beneath the sea, and sedimentation began again is in effect a 'fossil beach' formed as the sea gradually 'drowned' the land. Recognition of unconformities, and the missing strata they may represent, is crucial in working out the geological history of an area.

unconformities

ITQ 7 Now look at Figure 13. How many Ma are represented by the unconformity?

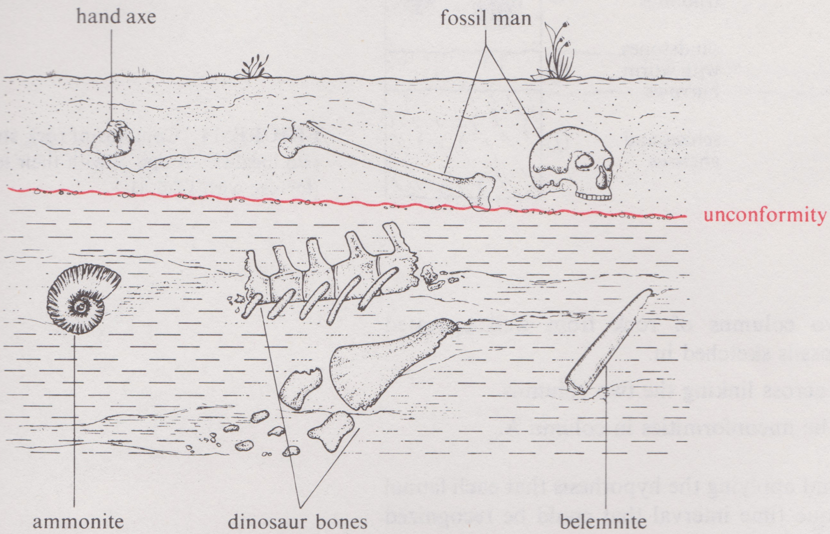


FIGURE 13 Hypothetical unconformity (for use with ITQ 7). The fossils in the lower bed became extinct at the end of the Cretaceous, long before Man appeared.

In the last years of the eighteenth century an Englishman, William Smith (1769–1839), an engineer and surveyor, who worked on canals, roads and drainage schemes all over England, found that he could recognize distinctive beds within rocks such as the Chalk on the North and South Downs, or within the coal-bearing strata in widely separated coalfields, and that *each group contained a particular assemblage of fossils quite distinctive from those of the strata above and below.*

He began to correlate apparently dissimilar sedimentary strata *because they contained similar fossils.* Furthermore he found that there was the *same succession of fossil assemblages from older to younger beds in all parts of the country.* He concluded that each stage of this succession of fossils represented a particular span of geological history, or a discrete length of time, and that rocks formed during that time would contain the same fossils wherever they occurred geographically. This he called the *principle of faunal succession*, and using it he was able to correlate widely separated outcrops of rock by the fossils they contained. An *outcrop* of rock is a piece of the solid rock strata (not a boulder) which is visible at the surface, so it 'crops out' through the soil and vegetation cover.

principle of faunal succession

outcrop

Now try a similar correlation exercise for yourself.

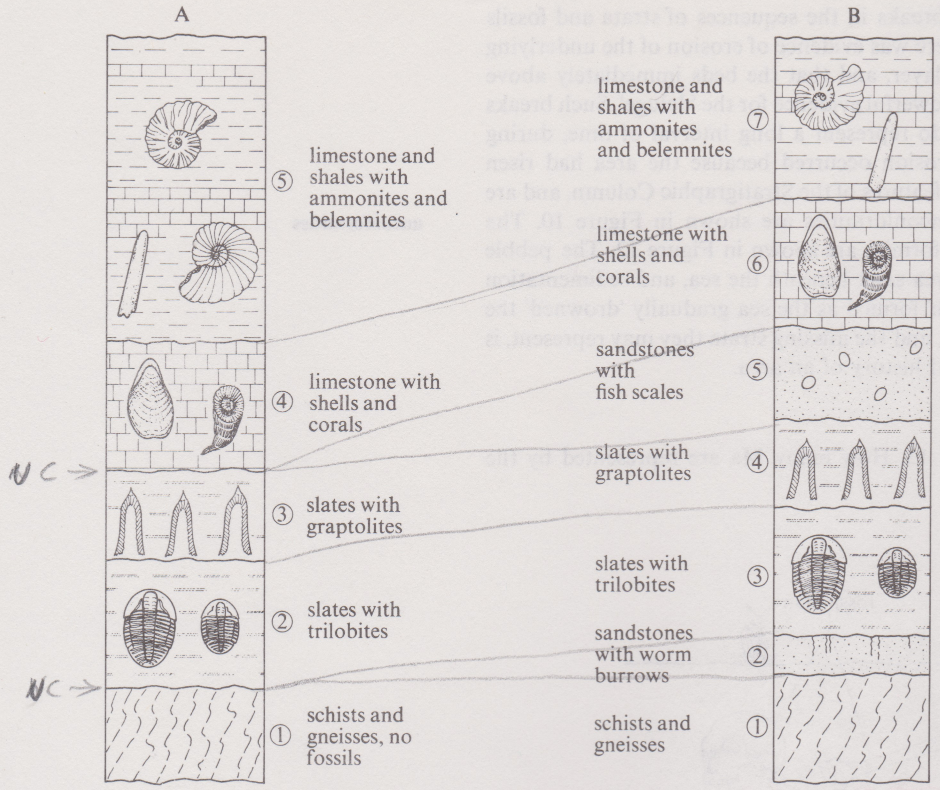


FIGURE 14 Columns of rock strata from two localities A and B with their fossils (for use with ITQ 8).

ITQ 8 Figure 14 shows two columns of rock from well-separated localities A and B, with their fossils sketched in.

(a) Draw lines of correlation across linking the two columns.

(b) Suggest where there may be unconformities in column A.

By using this method of correlation and applying the hypothesis that each faunal assemblage really represented a unique time interval that could be recognized anywhere, Smith was able to produce in 1815 the first *geological map* of England and Wales and part of Scotland. On a scale of five miles to the inch, it measured about 2 m by 3 m. He took an existing geographic map and showed the outcrops of each stratum by painting them in water colours. (Painting the geology onto a geographic base remained the main method of producing geological maps for more than a hundred years until it was superseded by colour printing.)

geological map

Having produced the map, Smith was then able to draw a geological section across it along the road from London to Snowdon, to show the relationship between the different strata. A simplified version of his 1817 section is shown as Figure 15, printed as a separate insert in this Unit.

If you look at Figure 15 you can see that a journey from London to North Wales would take you onto progressively older rocks. You can also see that each range of hills is caused by a particular geological stratum that is more resistant to erosion than the softer rocks forming the lowlands between. For example, the journey from London to Oxford starts and finishes on soft clays, the high ground of the North Downs and Chilterns between being caused by the harder Chalk.

Now that you have looked at the section, you can appreciate how Smith was able to produce the first nearly complete stratigraphic column for Britain, which accompanied his large map. We have reproduced a simplified version of this as Figure 16. Many of the terms he coined for rock strata are still in use today, although some have been modified, as you will find when you examine the modern Stratigraphic Column for southern Britain in Figure 17.

ITQ 9 Compare Smith's column, which has only the rock strata but no indication of the timescale involved, with the modern one (Figures 16 and 17) and with the generalized Stratigraphic Column (Figure 1). How much of geological history did Smith have essentially complete in his column?

Figures 16 and 17 are on pages 22 and 23.

In the last 160 years the main features of the geological map for strata younger than the Devonian drawn up single-handed by Smith have changed very little! He showed few details for rocks of the Lower Palaeozoic, which in Britain occur mainly in Wales. These are difficult to map in the field, since they consist largely of metamorphosed slates, which lack the distinctive marker horizons of the Mesozoic rocks where much of Smith's working life was spent. The details of the Lower Palaeozoic were not sorted out for another 65 years after Smith's work (see Section 3.5).

3.4 Uniformitarianism

James Hutton (1726–1797) contributed a great deal to the unravelling of Earth history, and his work dealt a blow to the religious ideas of great catastrophes as an explanation of the Earth's history. A remarkably perceptive observer of rocks in the field (Figure 18), Hutton thought that he recognized in the rocks of his native Scotland the results of processes taking place on the Earth's surface at present: processes such as erosion, volcanic activity and changes in climate.

FIGURE 18 James Hutton 'rather astonished at the shapes which his favourite rocks have suddenly taken'. (Caricature by John Kay, 1787. From the block in the possession of the Edinburgh Geological Society.)

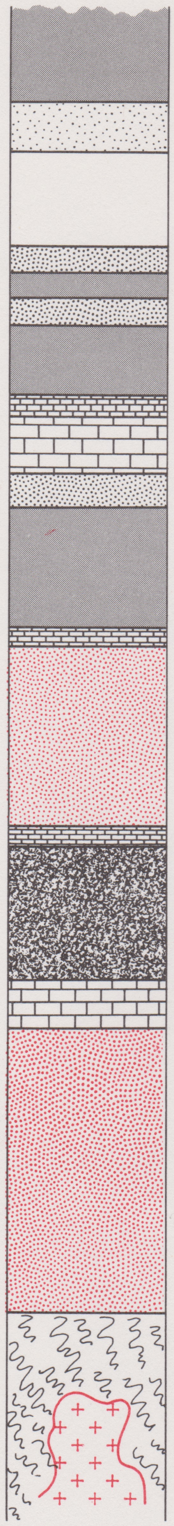
Let us look at these processes in turn.

Erosion of land is a continuous process and the broken-down fragments of rocks are transported to the sea where they eventually become sedimentary rocks. By looking at places where sediments are forming today, it is possible to interpret how old sedimentary rocks were formed. The removal of sediment from the land and its deposition in the sea is a process that can be measured. For example, it is possible to determine how much sediment per year is carried by major rivers. So, by looking at present-day sedimentary deposition, geologists can begin to estimate how long it must have taken for similar sediments to form in the past.

Volcanic activity Every day there is a volcano erupting somewhere on Earth, so it is possible to study volcanic processes and how volcanic rocks are forming today. This knowledge can then be used to interpret volcanic rocks such as those

The text continues on page 24.

Explanation of COLOURS on the MAP of Strata, taken in Succession from East to West, as the Strata occur.



London Clay, forming Highgate, Harrow, Shooters, and other detached hills........................	Part on which Lime is rarely used as a Manure.	Septarium, from which Parker's Roman cement is made.
Clay or Brick-earth, with interspersions of Sand and Gravel.		No building Stone in all this extensive district, but abundance of materials which make the best bricks and tiles in the island.
Chalk { Upper Part, soft, contains Flints..............		Flints, the best road materials.
Chalk { Under Part, hard, none......................		Good Lime for water cements.
Green Sand, parallel to edge of Chalk..................		Firestone, and other soft Stone, sometimes used for building.
Blue Marl, called in some places oak-tree clay.		
Purbeck Stone, Kentish Rag, and Limestone.		
Clunch Clay produces a strong clay soil, chiefly in pasture, in North Wilts and Vale of Bedford.		
Cornbrash, and Forest Marble Rock..................		Thin beds, used for rough Paving, makes tolerable roads.
Great Oolyte, Rock, which produces the Bath Freestone.		The finest building Stone in the island for Gothic and other architecture which requires nice workmanship.
Under Oolyte, of the vicinity of Bath and the Midlands.		
Blue Marl, under the best pastures of the midland counties.		
Blue Lias Limestone, now used for printing from MS. written on the stone.		
Red Marl and Gypsum, soft Sandstone and Salt Rocks and Springs.	Part on which Lime is generally used.	
Magnesian Limestone..............................		Small quantities of Copper and Lead.
Coal Measures, and the Rocks and Clays which accompany the Coal..		Grind-stones, Mill-stones, Paving-stone, Iron-stone and Fire-clay from the Coal Districts.
Derbyshire Limestone..............................		Lead, Copper, and Lapis Calaminaris – Marble.
Red and Dunstone, of the southern and northern parts, with interspersions of Limestone..........................		Some good building Stone.
Killas, or Slate and other strata, of the mountains on the western side of the island, with interspersions of Limestone.		The Limestone polished for Marble. Tin, Copper, Lead, and other minerals.
Granite and Gneiss................................		The finest building Stone in the island for bridges and other heavy work.

FIGURE 16 Stratigraphic column drawn up by William Smith (simplified after his original column, which accompanied his 1815 map). The ornaments used here have been changed from his original colours in the same way as in Figure 15. The column consists of the sequence of rock strata that Smith recognized from his field work, with observations about their character, uses, and effect on the landscape.

The text continues on page 21.

ERA	PERIOD	ROCK STRATA
CENOZOIC	Pleistocene	glacial materials
CENOZOIC (TERTIARY)	Oligocene and Pliocene	sands
CENOZOIC (TERTIARY)	Eocene	Bagshot Beds
		London Clay
		sands
MESOZOIC	Cretaceous	Chalk
		Greensands
		Weald Clay
		Hastings Beds
	Jurassic	Purbeck Beds
		Portland Beds
		Kimmeridge Clay
		Corallian
		Oxford Clay
		Cornbrash
		Oolite Series
		Lias
	Triassic	sand and marl
PALAEOZOIC	Permian	marl and limestone
	Carboniferous	Barren Measures
		Productive Coal Measures
		Millstone Grit
		Carboniferous Limestone
	Devonian	Upper Old Red Sandstone
		Middle Devonian Limestone
		Lower Old Red Sandstone
	Silurian	limestones and shales
	Ordovician	shales and volcanics
	Cambrian	slates and sandstones
PRECAMBRIAN	Precambrian	slates, metamorphic and igneous rock

FIGURE 17 Modern Stratigraphic Column for England and Wales. Geological time is shown in Eras and Periods as in Figure 1. To the right are the rock strata that can be recognized in the field.

FIGURE 19 Pillow lavas from widely separated localities and ages, both formed in the same way, by basalt lavas being erupted under the sea. (a) Lavas, *less than 1 Ma* old, from Iceland, showing internal structure of individual pillows. (b) Ancient lavas, about *85 Ma* old, from Oman, showing general form of pillows.

formed in north-west Scotland 60 Ma ago (like your Home Experiment Kit sample S3) or still older ones, formed about 400 Ma ago in the English Lake District.

Figure 19 shows an example of such a comparison for two pillow lavas (which form when basalt magma is erupted on the ocean floor, usually at a constructive plate margin, see Units 6 and 7). The pillows in Figure 19a, formed on the floor of the Atlantic in Iceland (TV 05), are less than a million years old, and identical pillows have been filmed recently as they formed from eruptions off Hawaii. The similar form of the pillows in Figure 19b enables us to be sure that they too were erupted on the sea-floor, though they were formed about 85 Ma ago in Oman.

Changes in climate From studies of erosion and transportation in different climates today we can deduce the climate under which rocks were formed in the past. For example, the similarities between the sand grains and the type of cross-bedding in the sandstone in Durham that you saw in TV 06 and those in sand dunes in the Sahara today indicate that 270 Ma ago sands in Britain were

being deposited in hot desert conditions. Present-day glaciers elsewhere can be seen to be eroding the landscape to leave characteristic land forms. Similar land forms found in Britain are interpreted as evidence that 20 000 years ago much of Britain was covered by an ice sheet.

This approach has already been referred to as the present being the key to the past. It was Hutton's work which first led to this *principle of uniformitarianism*, as it is called. Unlike many of his predecessors, Hutton always carefully reported actual observations and, in fact, was among the first to look at events in terms of what we would now call the geological cycle. He argued that mountains are shaped and ultimately destroyed by weathering and stream erosion, and that fragments of the rocks forming the mountains are carried to the sea. Hutton stated: 'There is not one step in all this ... that is not to be actually perceived' and then he tested the model by asking 'What more do we require?', to which he supplied the answer: 'Nothing but time'. Exactly how much time was involved in the Earth's history was a problem to be tackled later by other scientists, as you will see in Section 4.

uniformitarianism

3.5 The Stratigraphic Column

In examining both the generalized Stratigraphic Column (Figure 1) and the more detailed ones for Southern Britain (Figures 16 and 17) you may have wondered how the names of the various Periods were derived. The Palaeozoic Era is composed of six Periods; the three lower ones were first recognized in Wales but not without some difficulty and controversy.

Two pioneer geologists who attacked the problem of these older strata (the undifferentiated 'killas and slate' at the base of Smith's column) were Adam Sedgwick (1785–1873) and Roderick Murchison (1792–1871). Both began mapping these rocks in the summer of 1831 when there were as yet no rules for defining the Periods. Murchison concentrated his studies on South Wales, where he was able to use the Old Red Sandstone (Devonian) as a starting point in his mapping. You may have seen these red rocks which are typically developed in the Brecon Beacons. He started from the base of the Old Red Sandstone and established a sequence of strata, each group characterized by particular fossils, working down the Stratigraphic Column. For this sequence he introduced the name Silurian, from the name of a tribe, the Silures, who inhabited a part of South Wales at the time of the Roman occupation of Britain.

Sedgwick concentrated his studies in North Wales. He was at a disadvantage compared with Murchison because he did not have a reference level to work from in the Stratigraphic Column, like the Old Red Sandstone. But after several years he was able to work out a succession of the strata that he was mapping for which he proposed the name Cambrian, after Cambria, the Roman name for Wales.

At the time these two Periods were proposed, neither Murchison nor Sedgwick had any clear idea as to how they related to each other, whether they were entirely different strata, or if they overlapped, but each jealously guarded 'his' rocks and his name for the Period during which they had been formed.

Murchison (*South Wales*)	Sedgwick (*North Wales*)
Old Red Sandstone	?
Silurian	Cambrian
?	?

It was discovered eventually that the lower part of Murchison's Silurian contained the same fossils as those in the upper part of Sedgwick's Cambrian! This discovery led Murchison to conclude that all of Sedgwick's Upper Cambrian was merely a part of the Silurian—a conclusion strongly opposed by Sedgwick. The argument turned a warm friendship into enmity that lasted the lifetime of the two men. Finally in 1879, after both were dead, another geologist, Charles Lapworth, proposed the name Ordovician, after the tribe which had once occupied North Wales, to include the Upper Cambrian of Sedgwick and Lower Silurian of Murchison. The proposal was accepted and so the Ordovician now separates the rocks of the two rivals in the Stratigraphic Column.

If you are interested in the origins of the other Period names, have a look at Table 3. The Periods, once they had become established, together with other stratigraphic names, became part of an international geological terminology which could be applied all over the world.

TABLE 3 Origin of the names of the Periods in the Stratigraphic Column

Eras		Periods	Age of base in Ma	Country where defined	Author	Year defined	Derivation of name
CENOZOIC (recent life)		QUATERNARY					
		Holocene					Holos: whole*
		Pleistocene	2	England	Lyell	1829	Pleiston: most
		TERTIARY					
		Pliocene		England	Lyell	1833	Pleios: more
		Miocene		England	Lyell	1833	Meion: less
		Oligocene		Germany	Beyrich	1854	Oligos: few
		Eocene		England	Lyell	1833	Eos: dawn
		Palaeocene	65	Germany	Wilhelm Schimper	1874	Palaios: old
MESOZOIC (middle life)		CRETACEOUS	135	France	d'Halloy	1822	Creta: chalk
		JURASSIC	190	Switzerland	Humboldt	1795	Jura Mountains
		TRIASSIC	225	Germany	Alberti	1834	Threefold division recognized in Germany
PALAEOZOIC (ancient life)	UPPER	PERMIAN	270	Russia	Murchison	1841	Perm: Russia
	UPPER	CARBONIFEROUS	345	England	Conybeare and Phillips	1822	Coal: Carbon
	UPPER	DEVONIAN	395	England	Murchison and Sedgwick	1840	Devon
	LOWER	SILURIAN	430	Wales	Murchison	1835	Silures: Welsh border Celts
	LOWER	ORDOVICIAN	500	Wales	Lapworth	1879	Ordovices: Celts of N. Wales
	LOWER	CAMBRIAN	570	Wales	Sedgwick	1835	Cambria: Latin for Wales

* Sir Charles Lyell recognized that in the Cenozoic Era modern species appear as fossils, becoming progressively more abundant in younger sediments. (For example, 3 per cent of Eocene species are alive today, and as many as 30–50 per cent of Pliocene species exist today.) He therefore used Greek prefixes to subdivide the Cenozoic.

As you may have begun to realize, the Stratigraphic Column can be considered in several different ways, according to how the units of geological history are defined and measured. There are three main methods of doing this.

First to be recognized were distinctive sedimentary *rock units* such as the Chalk and the Coal Measures, and a column can be built up by arranging these units in their correct order to form a *rock-stratigraphic column.* (Smith's column, Figure 16, is an example of this.) The smallest unit in this column is an individual *bed* of a particular rock type, which is separated from the beds above and below by *bedding planes*, as shown in Figure 20. In different parts of the world, rock units of the same age may be quite different, reflecting the different conditions of deposition so that a locally distinctive rock unit cannot always be found elsewhere. A way of defining the Stratigraphic Column that can be applied more widely is therefore needed.

rock units

rock-stratigraphic column

bed

bedding planes

By using the time span of fossils, the Stratigraphic Column can be divided into *zones*, by the use of *zone fossils*. These define the *biostratigraphic column*. A zone may be defined for a short time-range such as that of an individual species which may have lived for less than a million years, up to that of a succession of related species which may have lived for several tens of Ma. Each Period is made up of a whole series of zones and zone fossils. In a crude sort of way the 'age of the dinosaurs' is such a biostratigraphic unit, albeit a large one, spanning more than one Period in the Stratigraphic Column (Figure 6).

zone, biostratigraphic column

Finally, it has been possible to get radiometric dates for some rocks in the Stratigraphic Column, and to express their ages in millions of years. Thus the time interval of each *Period* is now known in Ma, and so it is possible to say, for

FIGURE 20 Photograph of horizontal strata, to show bedding planes, separating individual beds of sedimentary rock. Beds of harder (lighter) limestone, alternate with softer (darker) shales, Lower Lias (Jurassic), Dorset.

example, that the Cambrian Period lasted for 70 Ma. This puts *actual dates* to the already established sequence of Periods of geological time, and is an example of an *absolute dating method*, although all such dates are subject to a degree of uncertainty.

absolute dating method

3.6 Objectives of Section 3

Now that you have completed this Section you should be able to achieve the following:

(a) Explain what is meant by the terms 'catastrophism', 'uniformitarianism', principles of 'superposition' and 'faunal succession', and be able to apply these correctly to descriptions of the work of early geologists such as Cuvier, Smith and Hutton. (SAQ 5)

(b) Be able to explain how features such as fossils, rock types, and age dates can all be used to prepare the local stratigraphic column for an area. (SAQ 6)

Now test your achievement of these Objectives by attempting the following SAQs.

SAQ 5 Did William Smith's application of the principle of faunal succession imply that he was interpreting Earth history in terms of either uniformitarianism or catastrophism?

SAQ 6 If you were asked to make a stratigraphic column of an area which consists largely of one rock type, a mudstone with some fossils, how would you define different units in your column, in terms of rock units, fossil zones, or time periods?

4 Early estimates of geological dates

Study comment Here the first attempts to quantify Earth history are presented. The actual dates which were calculated are much less important than the applications of the principle of uniformitarianism to begin to calculate the rates of geological processes. Again, this is a fairly straightforward Section, which continues the historical story of Section 3. It describes a few key contributions which took the history of the Earth from Archbishop Ussher's view (in the 1650s) of a world created in 4004 B.C. to the modern view of several thousands of millions of years.

By the 1840s the major divisions of the Stratigraphic Column had been worked out and geologists could begin to tackle the problem of how much time was represented by each unit in the Column. The principle of uniformitarianism propounded by Hutton, and that of faunal succession produced by Smith were put together by Sir Charles Lyell (1797–1875).

Lyell had little patience with geologists whose theories were not based on observation of present-day processes; he believed strongly in 'existing changes' (which we now call the principle of uniformitarianism). Lyell expressed his views on this very forcefully:

> It appeared that the earlier geologists had not only a scanty acquaintance with existing changes, but were singularly unconscious of the amount of their own ignorance.

And of catastrophism he wrote:

> Never was there a dogma more calculated to foster indolence, and to blunt the keen edge of curiosity than this assumption of the discordance between the ancient and existing causes of change.

To try to begin to work out the scope of geological time, Lyell looked for present-day rock-forming processes whose rates he could measure. From these direct observations, the time taken for the accumulation of comparable sedimentary rocks could then be estimated.

4.1 Lyell and the age of the Mississippi Delta

Lyell already had some idea of the rate of sedimentary accumulation in the Nile delta before he visited North America in the 1820s to look at the Mississippi:

> The mean annual thickness of a layer at Cairo cannot exceed that of a sheet of thin pasteboard, and a stratum of two or three feet must represent an accumulation of a thousand years.

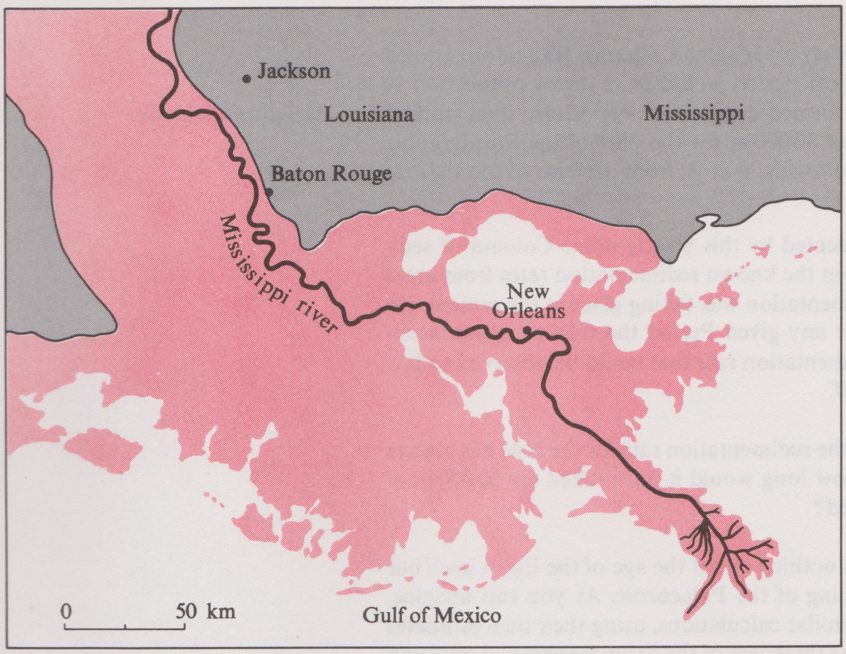
Lyell made the following estimates of the size and the present rate of sediment accumulation in the Mississippi delta (see Figure 21):

Area of deltaic deposits in Gulf of Mexico:	$3.4 \times 10^{10}\,\mathrm{m}^2$*
Area of deltaic depositions on land:	$1.6 \times 10^{10}\,\mathrm{m}^2$
Depth of deltaic deposits (average):	$1.6 \times 10^2\,\mathrm{m}$
Annual rate at which solid matter was brought into the delta:	$1.11 \times 10^8\,\mathrm{m}^3\,\mathrm{yr}^{-1}$.

To calculate an age all he did was to divide the total volume of the delta deposits by the annual amounts of sediment supplied by the river.

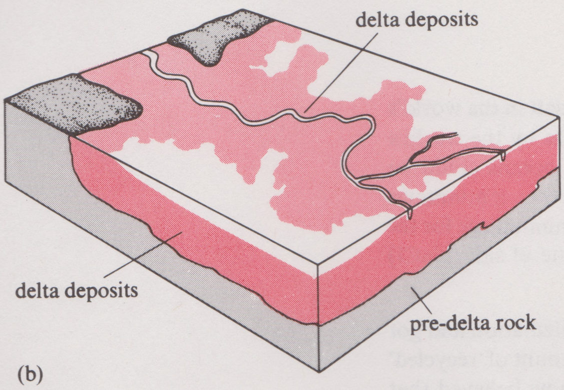
Examine the data and answer the following ITQ, which enables you to repeat his estimates, making the over-simple assumption that a cubic metre of sediment brought down by the river forms one cubic metre of sediment in the delta.

* We have changed his measurements into SI units to make the calculation simpler.

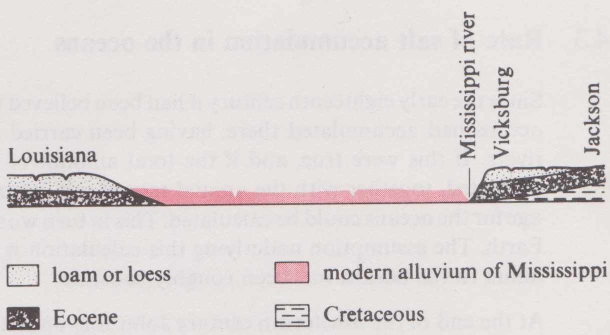


(a)

FIGURE 21 The Mississippi Delta. (a) General plan to show extent of deltaic deposits (red) above sea-level. (b) Block diagram to indicate the vast area covered by deltaic deposits below sea level. (c) Lyell's sketch section across the Mississippi River near Jackson showing how the delta deposits lie on top of the Eocene and Cretaceous sediments.



(b)



(c)

ITQ 10 (a) If you assume that the delta has built up at the present constant rate of sediment accumulation, how old is it?

(b) What is the annual thickening rate of the delta, assuming that sediment is evenly spread over all the delta each year?

So by *historic* standards the delta was extremely old, and it was accumulating somewhat faster than that of the Nile. But how old *geologically* was the delta was the next question Lyell asked, and to answer this he looked at the strata immediately beneath the delta.

Lyell's sketch section (Figure 21) shows he found the modern deltaic deposits (alluvium) lying on top of loam or loess which in turn overlay Eocene and Cretaceous strata. He found that the loam contained 'land, river and lake shells of species still inhabiting the same country'*, and so he concluded that it must be very recent geologically. The beds beneath were of Tertiary age, right at the top of Smith's Stratigraphic Column. So that although the deltaic deposits might be old in historical terms, they must be geologically *extremely young*. The Earth must, therefore, be many millions of years old, he concluded.

* It was evidence like this that led to Lyell's subdivision of the Cenozoic Era (Table 3).

4.2 Haughton's principle

Haughton's principle

In the last half of the nineteenth century an Irishman, Charles Haughton, argued that the relative age of each geological Period would be in direct proportion to the maximum thicknesses of strata formed during that Period. He then worked out a grand total thickness of about 50 000 m for the part of the Stratigraphic Column that contained recognizable fossils, that is, from the base of the Palaeozoic to the present.

He then argued that the time represented by this Stratigraphic Column of sedimentary rock could be estimated from the known sedimentation rates from areas such as deltas where the fastest sedimentation was taking place at the present. He assumed, not unreasonably, that for any given Period the thickest strata accumulated at the same maximum sedimentation rate that could be observed today. Now try this calculation for yourself.

ITQ 11 If you assume that the sedimentation rate for the Nile has always been 0.6 m per 1 000 years, how long would it have taken for 50 000 m of sediments to have accumulated?

Of course, estimates of this sort said nothing about the age of the Earth itself but only gave the time since the beginning of the Palaeozoic. As you can imagine, many different experts carried out similar calculations, using their own estimates both of the rate of deposition and the thickness of the Stratigraphic Column, and obtained answers ranging from a few tens of millions to hundreds of millions of years.

4.3 Rate of salt accumulation in the oceans

Since the early eighteenth century it had been believed that all the salt in the world's oceans had accumulated there, having been carried into the seas by the world's rivers. If this were true, and if the total amount of salt in the oceans could be estimated, together with the annual rate of salt influx by rivers, then a minimum age for the oceans could be calculated. This in turn would set a minimum age for the Earth. The assumption underlying this calculation is that the rate of salt (NaCl) influx to the oceans has been roughly constant.

At the end of the nineteenth century John Joly undertook this calculation and got an answer of 90 Ma, but we now know he underestimated the amount of 'recycled' salt which is blown back to the land by sea-spray. In fact it is now believed that only about 30 per cent of the sodium in river water is 'new' sodium, the rest has been recycled from the ocean by spray and rain.

ITQ 12 Would Joly's underestimation of the sea-spray blown inland have resulted in an over-estimate or under-estimate of the age of the Earth's oceans?

Consider next some modern data: estimates of 'new' sodium added to the ocean are: 6×10^7 tonnes per year, while the total sodium content of the oceans is about 15×10^{15} tonnes, calculated from the total volume of the oceans and average measured salinity values.

ITQ 13 How old does that make the oceans if Joly's calculation is repeated?

the sodium cycle

But obviously this figure is not a realistic estimate of the age of the oceans. Sodium liberated from rocks during weathering simply does not accumulate indefinitely in the oceans, but is recycled by a variety of processes. The *sodium cycle* is shown in Figure 22. Besides sodium returned to the land by sea-spray and rain, considerable amounts are removed from the oceans in sediments, which eventually can be returned to the land as rocks. Figure 22 represents the possible routes through which sodium passes through the geological cycle of erosion, transport and deposition.

If sodium were to be immediately removed from the oceans as soon as river water reached the sea, for example, by precipitation or reaction with sediments on the sea floor, then the sodium content of the ocean would be extremely low. If on the other hand *no* sodium was *ever* removed from solution in the ocean then

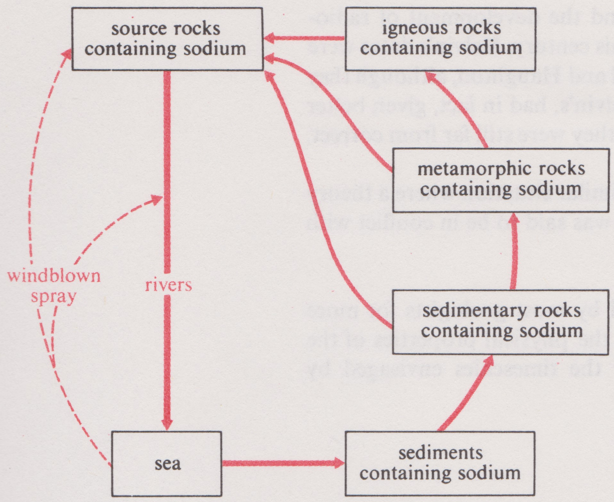


FIGURE 22 The sodium cycle. This diagram shows how sodium passes through the geological cycle of erosion, transportation and deposition. Solid lines indicate the main cycle, broken lines the recycling of sodium by sea-spray and rain.

the calculation of ITQ 13 would give the *age of the oceans* (assuming the rates of sodium addition had remained constant). If each ion of sodium brought to the oceans stayed in solution for 50 years on average before going either directly or indirectly into sedimentary, igneous or metamorphic rocks then at any time there would be '50 years' worth' of sodium dissolved in the oceans. Therefore, your answer to ITQ 13 means that on average each sodium ion stays in solution in the ocean for 250 Ma before being recycled. In other words, 250 Ma worth of sodium ions are accumulated in the oceans at any one time: the *residence time* of sodium in the oceans is 250 Ma.

residence time

This concept of residence time in a geochemical cycle is a very important one, as you will discover in Unit 32 when considering the hydrosphere and atmosphere and the accumulation of CO_2 in the present atmosphere due to burning of fossil fuels.

4.4 Kelvin and the cooling Earth

Towards the end of the nineteenth century a physicist, Lord Kelvin, calculated the age of the Earth from an entirely different point of view.

Kelvin clearly preferred quantitative methods:

> I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind.

(Lecture by Lord Kelvin to the Institute of Civil Engineers, 3 May 1883).

Kelvin assumed that the Earth had been cooling ever since its formation from a molten mass, by conducting heat to the surface and then by radiating it into space, and *that it had no continuing internal source of heat production.* A maximum age could therefore be calculated from the Earth's inferred present rate of cooling, calculated from the measured heat flow. His result was between 20 and 40 Ma for the age of the Earth.

Although many geologists disagreed with this age, the logic of his argument was difficult to refute, since it was based on the established laws of physics. At that time no one was aware of the main flaw in his argument, that heat *was* being produced inside the Earth.

> From your studies in the Course so far, do you know what this internal heat source is?
>
> Radioactive decay of the naturally occurring isotopes of elements like uranium, potassium and thorium.

With the discovery of radioactivity in the 1890s and the development of radioactive dating methods of rocks in the early years of this century, Kelvin's dates were abandoned. The geological ages calculated by Lyell and Haughton, although they were based on much more uncertain data than Kelvin's, had in fact, given better estimates of the Earth's age. But, as we now know, they were still far from correct.

Can you recall from earlier in the Course a similar situation where a theory was not accepted for many years because it was said to be in conflict with 'basic physics'?

Wegener's theory of continental drift was rejected by most geologists for more than 40 years because geophysicists thought that the physical properties of the mantle would not permit continents to drift on the timescales envisaged by Wegener.

4.5 Objectives of Section 4

Now that you have completed this Section you should be able to achieve the following:

(a) Make estimates of ages from given rates of simple geological processes and vice versa. (SAQs 7 and 8)

(b) Use data from simple given geological or geochemical cycles, such as that for sodium, to calculate geological rates and dates. (SAQ 9)

Now test your achievement of these Objectives by attempting the following SAQs.

SAQ 7 A modern estimate is that 550×10^6 tonnes of solid material is added to the Mississippi Delta each year. Assume that 1 cubic metre of sediment weighs 2.2 tonnes.

(a) How much does this differ from Lyell's figure?

(b) If Lyell had used this figure, would he have calculated an older or younger age for the delta?

SAQ 8 (a) Using the sedimentation rates estimated by Lyell for the Mississippi Delta, how long would it have taken for a stratigraphic column of 50 000 m of sediments, as estimated by Haughton, to have accumulated? (The sedimentation rate is given in the answer to ITQ 10(b).)

(b) Why would the figure you have calculated be likely to be an underestimate of the time represented by the stratigraphic column?

SAQ 9 (a) How does the fact that some salt from the ocean is carried back to the land in spray affect Joly's calculation of the age of the oceans from the sodium cycle?

(b) Can you suggest how plate tectonics affects the sodium cycle in Figure 22?

5 Radiometric dating

Study comment This Section briefly describes how the exponential decay of radioactive isotopes of certain elements which occur in some minerals* can be used to calculate ages for the formation of rocks. Since radiometric dating is a quantitative method, you will be asked to calculate actual ages yourself with your calculator or by log–linear graphs. This is the most tricky Section of this Unit and you should make sure you understand it by working carefully through the ITQs and answers.

5.1 Radiometric 'clocks'

Rocks that have minerals containing a radioactive isotope have a built-in 'clock' for measuring their age. The principle is very simple. The rates of decay of all the common radioactive isotopes are constant and are known from accurate laboratory measurements on pure samples. If the amount of a radioactive isotope present in a material when it was formed is known, then the age of that material is calculated from its present radioactivity, using the known decay rate for that isotope. You have already met this method of radioactive dating in Unit 10, Section 4.2, where the decay of $^{14}_{6}C$ in wood was described. In the case of wood, the amount of $^{14}_{6}C$ originally present is known, because $^{14}_{6}C$ is always roughly constant in the atmosphere and in living tissues which are equilibrium with the atmosphere. After death the decay of $^{14}_{6}C$ results in a progressive fall-off of radioactivity with time, and the age of the sample is given by the amount of radioactivity left. The half-life for this decay scheme is 5 730 years.

ITQ 14 From what you have learned of radioactivity in Unit 10, why is the $^{14}_{6}C$ method not suitable for dating most geological events?

Consider some of the naturally occurring radioactive isotopes which you met in Unit 10.

Which ones might be most useful for geological dating?

Isotope	Half-life
$^{22}_{11}Na$	2.6 years
$^{137}_{55}Cs$	30 years
$^{235}_{92}U$	7.0×10^{8} years
$^{40}_{19}K$	1.2×10^{9} years

Clearly the latter two, since they have half-lives of the same order as geological events.

However, the situation is slightly more complicated in the case of rocks than with plants dated by $^{14}_{6}C$. When they form, rocks may incorporate variable amounts of radioactive materials. It is necessary therefore to find some way of estimating the amount of radioactive isotope present in the rock at the time of its formation.

Most geological ages are calculated from radioactive decay series where the original '*parent*' *isotope* decays to give a stable '*daughter*' *isotope*. To calculate the age of a mineral grain, it is necessary to find out how much of the parent isotope has decayed since the mineral was formed. This is normally done by measuring the amount of daughter isotope present, as well as the amount of parent isotope left, to get the *parent* : *daughter ratio*.

parent isotope, daughter isotope

parent : daughter ratio

* Minerals are the naturally occurring compounds of roughly fixed chemical compositions of which rocks are formed, and are further discussed in Unit 27.

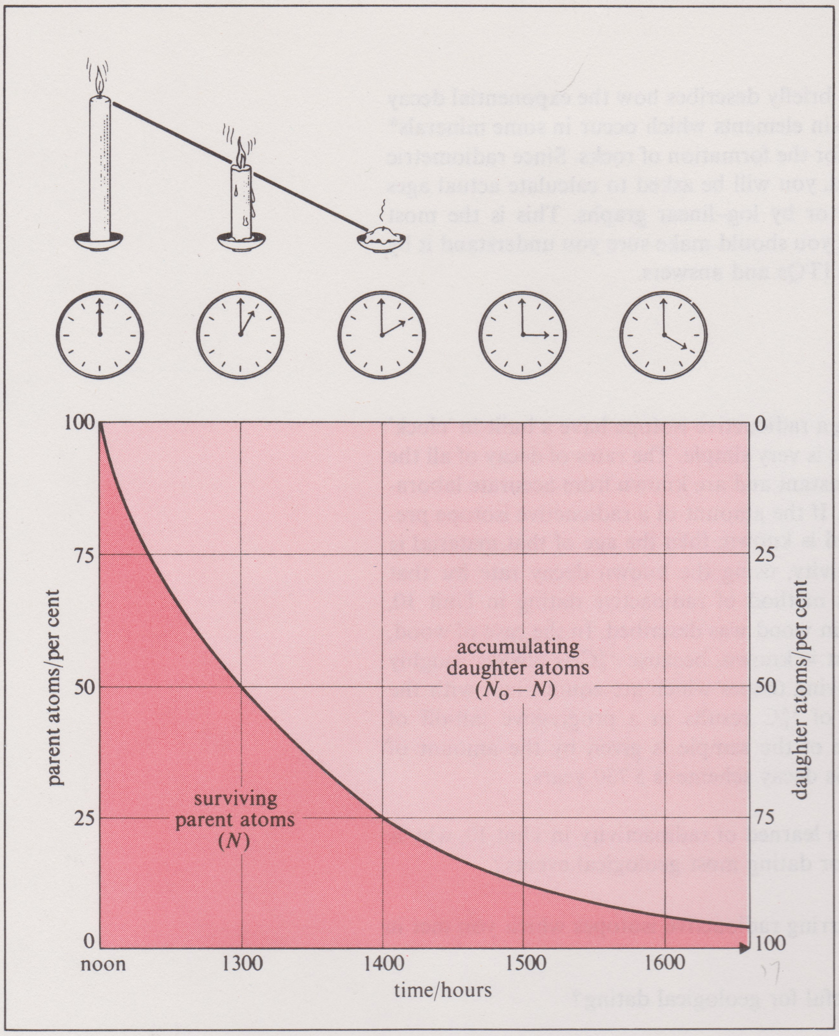


FIGURE 23 Comparison of a linear decay process (burning candle) with exponential decay (radioactive decay). N_0 = original number of parent atoms; N = number of parent atoms at any subsequent time.

exponential decay

The nature of the radioactive decay process compared with a burning candle is shown in Figure 23. Note that the rate of radioactive decay is *exponential*, whereas the decay of the candle is linear.

You have met exponential processes before in Unit 18, Section 4, when considering the growth potential of organisms.

> Can you recall the formula that expresses the numbers of offspring produced (N) after n generations have bred, if the population doubles in size in each generation?

$$N = 2^n$$

With radioactive decay the radioactivity *decreases* with time. If N_0 is the number of original parent atoms, and the number of those surviving after any time is called N, the decay process can be expressed in a similar way:

$$N = N_0 \times (\tfrac{1}{2})^n \qquad (1)$$

where n is the number of half-lives of the decay scheme concerned. The half-life is the time taken for half the original material to decay.

Look at Figure 23. In the first hour, from noon to 1300, while half the candle burnt away, half the radioactive parent decayed. But during the second hour, from 1300 to 1400, while the bottom half of the candle burnt away, only a further quarter of the original radioactive parent decayed (half of the total that was left at 1300 hours).

And so at 1600 hours 1/16 of the original parent atoms are left and 15/16 of the total possible daughter atoms have been formed. You have already met a graph of

this shape when considering $^{14}_{6}C$ dating (Unit 10, Figure 13). The reason why radioactive decay has this exponential form does not concern us here. You will be studying radioactive decay processes in more detail in Unit 30*.

Look at Figure 23. What is the half-life of this radioactive isotope?

One hour. From 1200 noon to 1300 hours the amount of parent isotope fell to half of its original value.

ITQ 15 If the original sample in Figure 23 contained 10^{10} atoms of parent isotope at noon, how many would remain at 1800 hours, that is, after six half-lives?

From the answer to ITQ 15 you may have realized that the easy way to find the number of atoms (N) remaining after a given number of half-lives (n) is to use equation 1:

$$N = N_0 \times (\tfrac{1}{2})^n \qquad (1)^*$$

There is another way to use equation 1. Look again at Figure 23. This time suppose you did not know how long the radioactive decay had been going on, but had been told that the half-life was 1 hour, and that the present parent : daughter ratio was 1 : 500.

Can you calculate when the decay started (that is, the age of the sample)?

Present parent : daughter ratio = 1 : 500
The original number of parent atoms $(N_0) = 500 + 1 = 501$ (since one parent atom decays to give one daughter atom)
The present number of parent atoms $(N) = 1$
The present number of daughter atoms $(N_0 - N) = 500$

We need to find n, the number of half-lives that have elapsed.

$$N = N_0 \times (\tfrac{1}{2})^n \qquad (1)^*$$

Rearranging, $$\frac{N}{N_0} = \left(\frac{1}{2}\right)^n$$

Taking logs, $$\log\left(\frac{N}{N_0}\right) = n \log\left(\frac{1}{2}\right)$$

Therefore $$n = \log\left(\frac{N}{N_0}\right) \Big/ \log\left(\frac{1}{2}\right) \qquad (2)$$

Using equation 2, $$n = \log\left(\frac{1}{501}\right) \Big/ \log\left(\frac{1}{2}\right)$$

Using your calculator, *key*: 501, $\frac{1}{x}$, log, ÷, 2, $\frac{1}{x}$, log = 8.9686.

So the number of half-lives, $n = 8.97$.

The half-life is known to be one hour, so the age of the sample is 8.97 hours.

You have just calculated a radiometric age in terms of the number of half-lives (n), from the present parent : daughter ratio $(N/N_0 - N)$. To arrive at the actual age of the sample in hours you then multiplied n by the half-life, one hour.

Equation 2 is generally used for calculations of this type.

* You can regard radioactive decay in terms of the *probability* of a radioactive nucleus decaying in a given time interval. A rough analogy to a collection of radioactive isotope nuclei decaying is a large stack of pennies which are tossed at a regular time interval, say each hour, all 'heads' being rejected (decayed daughter isotopes), all tail pennies being kept and retossed (parent isotopes). The half-life for this 'decay' scheme is clearly the tossing interval, 1 hour.

Normally the age of a geological sample, t, is calculated in Ma, so that n in equation 2 has to be multiplied by the half-life of the radioactive decay process, τ (tau; also expressed in Ma): $t = n \times \tau$. Therefore, to get the age in Ma we replace n by t/τ in equation 2 to give:

tau, τ, half-life of decay process

$$\frac{t}{\tau} = \log\left(\frac{N}{N_0}\right)\Big/\log\left(\frac{1}{2}\right) \qquad (3)$$

It is also possible to work out ages from exactly the same data by plotting the information on a graph. When one quantity which changes by several orders of magnitude is to be plotted against another which changes more slowly, as in this example, where the number of atoms decreases by a factor of over a thousand in 10 hours, it is convenient to plot the rapidly changing quantity on a log scale. (This is the same thing as plotting the log of the quantity on a linear scale.) You have already done this in Units 18 and 21, and it is explained in detail in *HED**, Section 3.6 (see Figures 29 and 30).

HED

Now try this method for yourself, using Figure 24, to replot the data from Figure 23.

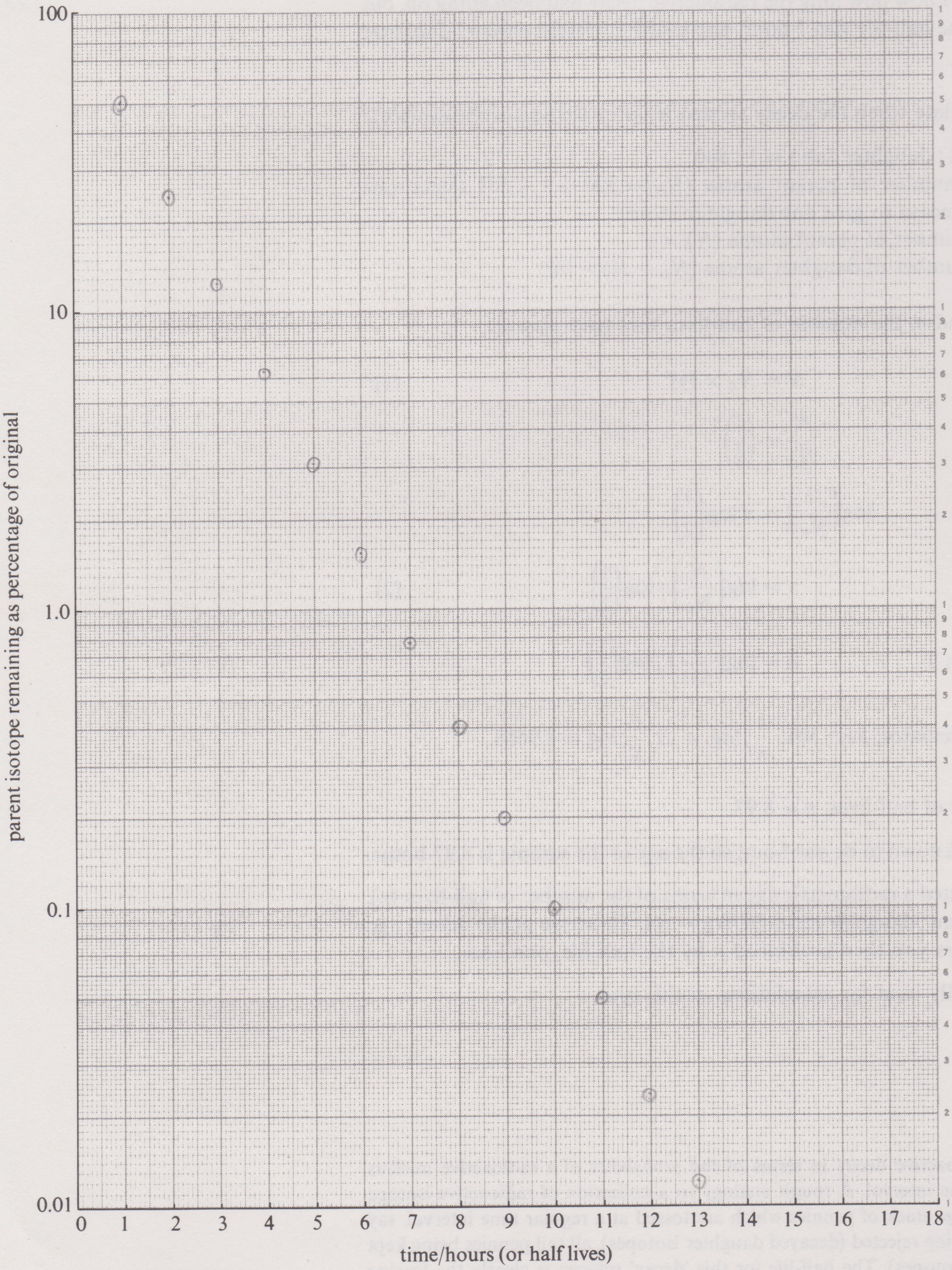


FIGURE 24 Log–linear graph for use with ITQ 16.

Plot the amount of parent isotope remaining against time on Figure 24. Look again at Figure 23. Clearly you should start at time 0 with 100 per cent of the parent isotope, that is, at the top left-hand corner. Since the half-life here is one hour, the horizontal scale can be read in either half-lives or hours.

ITQ 16 (a) How long does it take for the parent : daughter ratio to be 1 : 500?

(b) How long does it take for the parent : daughter ratio to be 1 : 5 000?

In Figure 24 the horizontal scale is in *hours* (half-lives) and the vertical scale denotes percentage of parent isotope remaining. This choice of units is arbitrary. You could equally well have plotted the actual mass of parent isotope remaining as a function of time measured in either seconds or days, but the graph *would still have been a straight line on log–linear paper*, since you are plotting an exponential curve.

HED

Obviously, a radiometric clock must operate on a timescale of the same order of magnitude as the process being timed. The amounts of radioactive isotopes in most rocks are very small, usually measured in parts per million. Furthermore, as you have seen in ITQ 16(b), after 12 half-lives the parent : daughter ratio falls to 1 : 5 000, that is, the parent isotope essentially disappears. To use the parent : daughter ratio for dating we need to know the amounts of both present very accurately. If they were in the ratio 1 : 5 000 this would clearly present severe measuring problems! For this reason all radiometric ages carry an uncertainty, usually ± 1 to 2 per cent, due largely to the difficulties in measuring the very small quantities of isotopes present in the samples.

5.2 Geological radiometric clocks

There are several radioactive decay processes that have been used for geological dating, and a selection are shown in Table 4:

TABLE 4 Commonly used radioactive dating processes*

Parent isotope		Daughter isotope	Half-life
$^{238}_{92}U$	⟶	$^{206}_{82}Pb$	4 467 Ma
$^{235}_{92}U$	⟶	$^{207}_{82}Pb$	704 Ma
$^{40}_{19}K$	⟶	$^{40}_{18}Ar$	1 193 Ma
$^{87}_{37}Rb$	⟶	$^{87}_{38}Sr$	48 800 Ma

* The details of these decay processes need not concern you now. An example of the complexity of one, $^{238}_{92}U$, is given in Section 6.5 of Unit 30, where you will see that the decay of $^{238}_{92}U$ to $^{234}_{90}Th$ given in Section 4.1 of Unit 10, is only the first step in the decay. The final stable daughter isotope $^{206}_{82}Pb$ is what is used for calculating geological dates.

So how is a rock sample dated? What kind of mineral can be used for dating?

Clearly a mineral is needed that contained atoms of a radioactive isotope when it orginally crystallized. Each parent atom eventually decays to a daughter isotope which is retained in the same crystal. Suppose we find an igneous rock containing a uranium-rich mineral and that when it initially crystallized, it did not incorporate any lead into the crystals. As time passed, some of the uranium was converted to lead by radioactive decay. To find out how old the rock is, samples of the mineral can be dissolved to get the uranium and lead into a solution. The parent : daughter ratios of the isotopes $^{235}_{92}U : ^{207}_{82}Pb$ and $^{238}_{92}U : ^{206}_{82}Pb$ can then be measured with a mass spectrometer, in much the same way as the isotopes of neon were analysed in TV 10.

Consider the decay of $^{235}_{92}U$ to $^{207}_{82}Pb$. Since one atom of uranium decays to yield one atom of lead, and both the amounts of parent (N) and daughter ($N_0 - N$) isotopes present now can be measured, the age of the sample can be calculated

from the known half-life of the parent isotope (τ), 704 Ma, by using equation 3. Figure 25 shows diagrammatically how the proportions of these two isotopes have changed with time.

This simple dating procedure will work only if the following assumptions are true:

(a) there is no production of $^{235}_{92}U$ or $^{207}_{82}Pb$ by any other radioactive decay process;

(b) $^{235}_{92}U$ decays to yield only $^{207}_{82}Pb$;

(c) all the $^{235}_{92}U$ and $^{207}_{82}Pb$ have been *retained within the mineral* since its time of formation;

(d) and that no $^{207}_{82}Pb$ was present originally.

For these particular decay processes these assumptions are generally valid.

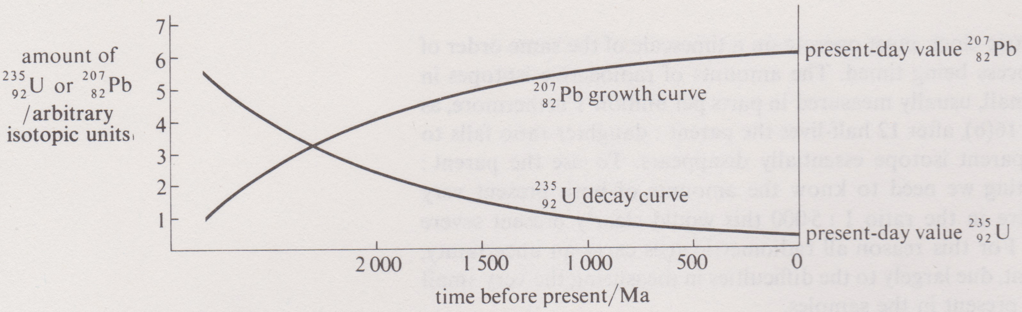


FIGURE 25 The changing proportions of $^{235}_{92}U$ and $^{207}_{82}Pb$ with time. The decay curve for the parent isotope, $^{235}_{92}U$, is a mirror image of the growth curve of the daughter isotope, $^{207}_{82}Pb$.

704 Ma

ITQ 17 (a) A grain of an originally lead-free mineral that contained uranium was found to have equal isotopic proportions of $^{235}_{92}U$ and $^{207}_{82}Pb$. How old is the mineral grain? (Refer to Table 4).

2816 Ma

(b) If a similar mineral from another rock contained fifteen times as much $^{207}_{82}Pb$ as $^{235}_{92}U$, how old is it?

The simplest rocks to use for radiometric dating are igneous ones, in which all the mineral grains are formed by crystallization from the magma at about the same time. If a mineral that contained no daughter isotope when it crystallized is isolated today, the radiometric date that is determined is the date of crystallization, when the parent isotope was 'locked up' in a crystal and the radiometric clock 'started to tick' inside the mineral.

In metamorphic rocks, in which some recrystallization of the minerals may have occurred as a result of the rocks being heated up, radiometric ages may reflect the date at which a metamorphic event took place. If the whole rock recrystallizes during metamorphism, then any daughter atoms produced before that time may escape from the mineral grain in which they were formed to move away from the remaining parent isotope and become incorporated into new minerals. The radioactive parent may also crystallize into new minerals which do not contain any of these daughter atoms. Thus the radiometric clock has been restarted, and so age determinations for that mineral will give the date of the metamorphism.

If recrystallization is incomplete during metamorphism, and only partial separation of parent and daughter isotopes occurs, then ages intermediate between that of the original rock and the time of metamorphism may be found. A very erratic pattern of ages can result, depending on the extent of this partial isotope separation.

Can you see why it is normally difficult to date sedimentary rocks by radioactive methods?

Because sediments are normally formed by the accumulation of pre-existing mineral grains, the radiometric age determined from a sedimentary mineral would normally be that of the rock from which the grain came. Thus a particular grain in a sandstone may yield a radiometric age of the igneous rock from which the original mineral grain came, and could be hundreds of Ma older than the sediment.

You may be able to consider the problems of dating sedimentary rocks again after studying sedimentary rock-forming processes in Unit 27, while the way in which radiometric dates on igneous rocks can be used indirectly to calibrate the sediments of the Stratigraphic Column is the subject of Section 6 of this Unit.

5.3 How old is the Earth?

Once geologists had discovered how to put precise radiometric ages on rocks, they could begin to sort out the history of the Earth's crust far back in time, using dated igneous rocks which crystallized up to several thousand Ma ago. One approach to the question of the Earth's age is to find out the age of the oldest parts of the crust that are now exposed at the surface. The Earth must clearly be older than the oldest dated crustal rocks! The oldest rocks that have been dated so far are crystalline gneisses and schists (highly metamorphosed igneous or sedimentary rocks) from Greenland, yielding maximum ages of about 3 800 Ma. Is this likely to be the age of the 'original' crust of the Earth, or could the Earth be very much older? You will study what we know of the Earth's formation and its early history in Unit 28. Until we know more of the processes by which the Earth was formed, all we can say from this is that the Earth must be at least 3 800 Ma old.

Can isotopic data be used to set any *upper* age limit for the Earth? In Section 5.4 we consider the evidence obtained from studying the proportions of the isotopes of lead in the Earth, and in Section 5.5 we look at the lead isotopic composition of meteorites.

5.4 The evidence from lead isotopes

There are four main isotopes of lead found in rocks:

$^{204}_{82}Pb$ not formed from any known radioactive decay process;

$^{206}_{82}Pb$ formed from $^{238}_{92}U$ by radioactive decay;

$^{207}_{82}Pb$ formed from $^{235}_{92}U$ by radioactive decay;

$^{208}_{82}Pb$ produced by radioactive decay of thorium ($^{232}_{90}Th$), not considered further here.

It follows that some, if not all, of the $^{206}_{82}Pb$ and $^{207}_{82}Pb$ have been produced from $^{238}_{92}U$ and $^{235}_{92}U$ by radioactive decay in the Earth since its formation, so that the amounts of $^{206}_{82}Pb$ and $^{207}_{82}Pb$ in the Earth as a whole must have increased through geological time up to their present abundances. The *rate* at which these two uranium isotopes decay is known (Table 4), so that by measuring their present-day abundances in the Earth as a whole one can work out how much of each was present at any time earlier in the Earth's history, and how much $^{206}_{82}Pb$ and $^{207}_{82}Pb$ have been produced by their decay. Figure 26 shows the uranium decay curves, each of which has a corresponding lead growth curve (not shown), as in Figure 25.

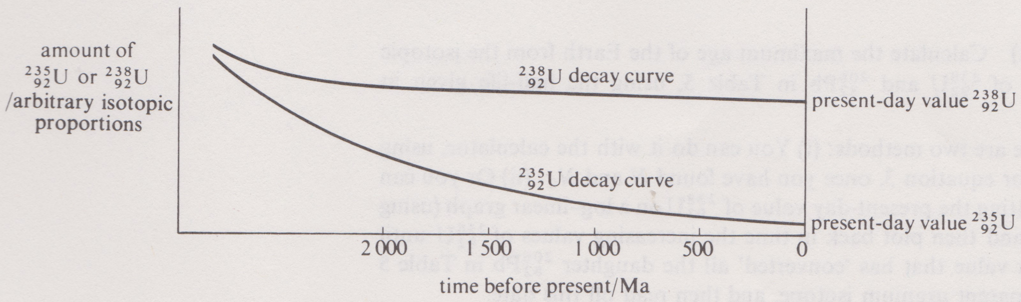


FIGURE 26 Comparative decay curves for $^{238}_{92}U$ and $^{235}_{92}U$ constructed back in time from their present-day abundances in the Earth as a whole, by using the appropriate half-lives from Table 4.

If one can also establish reliable values for the present-day abundances of $^{206}_{82}Pb$ and $^{207}_{82}Pb$ in the Earth as a whole, one can calculate how long it would have taken to produce these lead isotopes entirely from the decay of their parent uranium isotopes by constructing lead growth curves backwards from these values. In

principle this method can be used to set a maximum age for the Earth. However, there is no reason why there should not have been some $^{206}_{82}Pb$ and $^{207}_{82}Pb$ present in the material from which the Earth formed, so this method need not yield an exact age for the Earth, but only set a *maximum value.*

Geologists have found that the sediments currently forming in the deep oceans are the best places to measure present-day isotopic compositions representative of the whole Earth, since the ocean floors receive sediment from all types of rock exposed at the Earth's surface, and no large amount of sediment from any local area. The long residence time which many materials have in the deep ocean (remember the 250 Ma of the sodium cycle), means that any short-term fluctuations are smoothed out. You have already learned in Units 6 and 7 that plate tectonic processes continuously create new crust by generation of magma from the mantle, and so these isotope values are probably *reasonably representative of the mantle, and hence of the Earth as a whole.*

The present-day isotopic-abundance ratios for lead and uranium isotopes for deep ocean sediments are shown in Table 5.

TABLE 5 Present-day lead and uranium isotopic-abundance ratios in deep-ocean sediments (arbitrary scale of isotopic proportions with $^{204}_{82}Pb$ set at unity*)

$^{204}_{82}Pb$	1
$^{206}_{82}Pb$	18.5
$^{207}_{82}Pb$	15.6
$^{235}_{92}U$	0.0725
$^{238}_{92}U$	10.0

* It is assumed that none of the $^{204}_{82}Pb$ has been formed by radioactive decay, since no decay process is known that produces this isotope. Therefore the amount of $^{204}_{82}Pb$ is always set to unity, to enable the isotopic abundances of lead from different types of sediment to be compared.

Starting from these proportions, the amounts of uranium parent isotopes and lead daughter isotopes present at any time in the past can be calculated by using the known half-lives for the decay schemes concerned. For example, a thousand Ma ago there would have been more than twice as much $^{235}_{92}U$ present in the Earth and correspondingly less $^{207}_{82}Pb$, while there would have been very little change in the amounts of $^{238}_{92}U$ and $^{206}_{82}Pb$ (see Figure 26).

To set a maximum age for the Earth from these isotopic proportions, it is possible to do two separate calculations, one for $^{238}_{92}U \longrightarrow {}^{206}_{82}Pb$, and another for $^{235}_{92}U \longrightarrow {}^{207}_{82}Pb$. The assumption is made that the values in Table 5 are representative of the Earth as a whole, and that none of these four isotopes has been added to or removed from the Earth since its formation. Using the values for the half-lives given in Table 4, see if you can calculate the time necessary to generate these daughter leads from their respective uranium parents by doing ITQ 18.

ITQ 18 (a) Calculate the maximum age of the Earth from the isotopic proportions of $^{238}_{92}U$ and $^{206}_{82}Pb$ in Table 5, using the half-life given in Table 4.

Clue There are two methods: (i) You can do it with the calculator, using equation 2 or equation 3, once you have found N and N_0. (ii) Or you can start by plotting the present-day value of $^{238}_{92}U$ on a log-linear graph (using Figure 27) and then plot back in time the increasing values of $^{238}_{92}U$ until you reach a value that has 'converted' all the daughter $^{206}_{82}Pb$ in Table 5 back to its parent uranium isotope, and then read off this date.

(b) Now repeat the calculation of the Earth's maximum age from the isotopic proportions of $^{235}_{92}U$ and $^{207}_{82}Pb$.

Thus, if *all* the $^{207}_{82}Pb$ has come from radioactive decay of $^{235}_{92}U$ since the Earth was formed, this sets a maximum age for the Earth of 5 460 Ma. It cannot possibly be older than this or there would have been *more* $^{207}_{82}Pb$ formed from $^{235}_{92}U$ than actually exists today! The comparable figure for $^{238}_{92}U \longrightarrow {}^{206}_{82}Pb$ is 6 750 Ma.

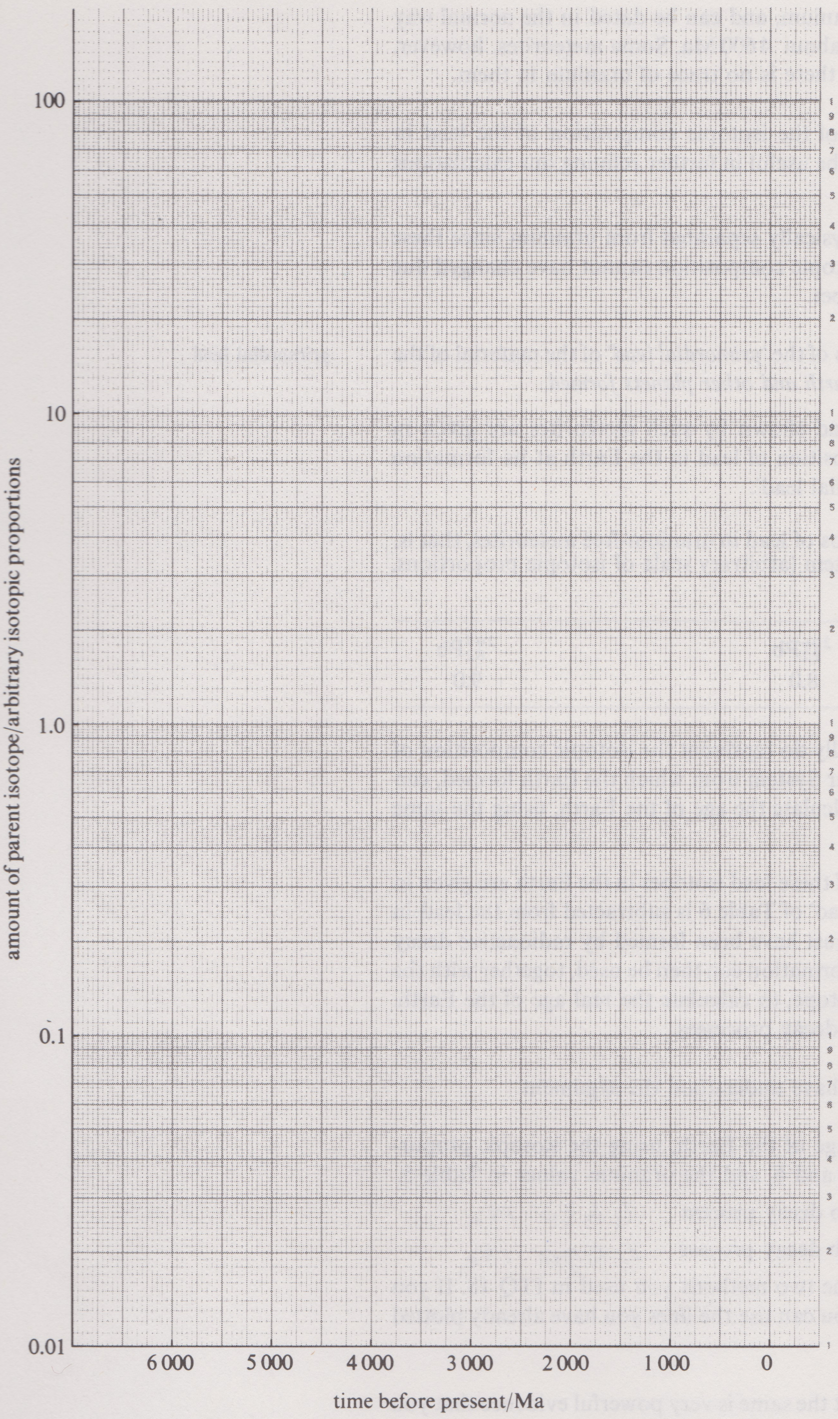


FIGURE 27 Log–linear graph for use with ITQs 18 and 19. The amounts of isotopes shown on this graph are in the same units as in Table 5, that is, with $^{204}_{82}Pb = 1$.

Two conclusions follow from this:

1 The maximum age of the Earth is about 5 500 Ma.

2 Some of the $^{206}_{82}Pb$ must have been present in the material from which the Earth was formed. If there was also some $^{207}_{82}Pb$ present in this original material the Earth must, of course, *be even younger than 5 500 Ma.*

5.5 The evidence from meteorites

As you already know from Unit 4, it is believed that meteorites were formed by similar processes to those which formed the Earth, and provide samples representative of the various layers within the Earth at levels too deep ever to be examined. It is very likely that meteorites, or the parent bodies from which they were formed, originated at the same time as the Earth and other similar planets, and in Unit 28 you will consider further the evidence for this conclusion. Many minerals in

meteorites contain both lead and uranium, and can be dated in the normal way described above: they yield ages of about 4 600 Ma. Some meteorites, however, have minerals that contain lead, but there is no trace of uranium in them.

Can you see how an analysis of the isotopic composition of the lead in uranium-free meteorites could be useful in further refining our calculations of the age of the Earth?

Because this lead has been physically separated from uranium since these meteorites were formed, its isotopic composition cannot have changed due to the decay of uranium isotopes.

Such meteorites must give us samples of the '*primordial lead*' of the material of the Solar System *at the time when the Earth and other planets formed.*

primordial lead

The isotopic-abundance ratios of lead shown by such meteorites are given in Table 6. The original isotopic composition of lead in the Earth at its formation must have been that of this 'primordial lead'.

TABLE 6 Isotopic-abundance ratios of lead in uranium-free meteorites, that is, the 'primordial lead' of the Solar System (arbitrary scale of isotopic proportions, with $^{204}_{82}Pb$ set at unity)

$^{204}_{82}Pb$	$^{206}_{82}Pb$	$^{207}_{82}Pb$
1.0	8.0	9.0

Assuming that these values really do represent the isotopic composition of the primordial lead of the Solar System from which the Earth formed, can you see how it is possible to calculate the age of the Earth, using the same method as in ITQ 18?

The present-day abundances of these lead isotopes in the Earth are given in Table 5, so if the 'primordial lead' of Table 6 is subtracted from the lead in Table 5, the remaining lead must have been formed by radioactive decay *since the Earth formed*. This information can then be used, together with the amount of parent uranium isotope, to calculate the real age of the Earth. You can use either of the two decay processes.

Now try this to make sure that you have understood the argument.

ITQ 19 Work out the real age of the Earth, using the isotopic proportions of lead given in Tables 5 and 6, and the uranium values in Table 5.

(a) from $^{238}_{92}U \longrightarrow {}^{206}_{82}Pb$ decay process 4630 Ma

(b) from $^{235}_{92}U \longrightarrow {}^{207}_{82}Pb$ decay process 4590 Ma

Clue You can use either of the two methods you used in ITQ 18. If you choose the log–linear graph, you can use the lines you have already plotted on Figure 27.

The fact that both answers are almost the same is very powerful evidence that you are on the right track!

If the Earth was formed at about 4 600 Ma ago from material containing the same isotopic composition of lead as uranium-free meteorites, and since then has developed additional $^{206}_{82}Pb$ and $^{207}_{82}Pb$ from the decay of $^{238}_{92}U$ and $^{235}_{92}U$, then all the isotopic data in Tables 5 and 6 make sense. Further confirmation that the Earth and other planetary bodies were created 4 600 Ma ago was provided by age determination carried out on lunar samples: the oldest Moon rocks were also found to be 4 600 Ma old.

5.6 Objectives of Section 5

Now that you have completed this Section you should be able to achieve the following:

(a) Be able to explain in simple terms how geological materials can be dated by radiometric methods, and be able to choose the most appropriate from several possible radiometric 'clocks' for a given dating problem. (SAQ 10)

(b) Calculate a radiometric age from a given half-life and parent: daughter ratio for the isotopes involved in a decay scheme, using the decay equation

$$N = N_0 \times \left(\frac{1}{2}\right)^n \quad \text{or} \quad \frac{t}{\tau} = \log\left(\frac{N}{N_0}\right) \Big/ \log\left(\frac{1}{2}\right)$$

which you should be able to derive or recall, or by plotting a graph on log–linear paper. (SAQ 11)

Now test your achievement of these Objectives by attempting the following SAQs.

SAQ 10 Look at Figure 26, which shows the changing proportions of $^{235}_{92}U$ and $^{238}_{92}U$ backwards in time from the present. If you had a series of samples of uranium-containing minerals which you thought were *about* 500 Ma old, would $^{235}_{92}U \longrightarrow {}^{207}_{82}Pb$ or $^{238}_{92}U \longrightarrow {}^{206}_{82}Pb$ be the better radiometric clock to use for measuring the most accurate dates?

SAQ 11 If a mineral sample from an igneous rock gave an isotopic ratio of $^{207}_{82}Pb : {}^{235}_{92}U$ of 20 : 1, how old was the rock from which it came?

6 Calibrating the Stratigraphic Column

6.1 Igneous rocks as calibration points

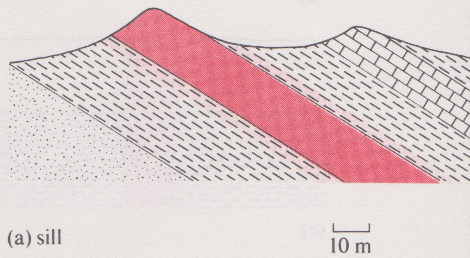
As an igneous magma cools and minerals containing a radioactive isotope crystallize, the radiogenic 'clock' is started in the rock, so that at any time subsequently the age of cooling can be determined by the methods described in Section 5. Although igneous rocks are relatively rarely found interstratified with sedimentary rock that can be dated by fossils in the Stratigraphic Column, when this happens the igneous ages provide crucial calibration points, since they can give an exact age in millions of years to that part of the Stratigraphic Column. The best examples are lavas, which clearly *postdate* the rocks beneath and *predate* subsequent strata; in other words, their stratigraphic age relationships are exactly the same as for the adjacent beds of sediment, to which they provide an 'absolute' age.

But not all magma reaches the Earth's surface, and if magma solidifies by infilling fissures or larger spaces in the crust the igneous rocks that result can be shown to be later than the surrounding rocks because the igneous rocks may *cut across pre-existing structures such as bedding planes*. The heat and fluids from cooling magma may also cause drastic chemical and physical changes in the surrounding rocks. This process is called *contact metamorphism*. Often an intrusive rock itself may show the effects of rapid cooling where it has come in contact with the surrounding strata.

An igneous rock which is intruded as a sheet along a bedding plane is called a *sill*. Sills are often from a few metres to a few tens of metres in thickness and spread over an area of many tens or hundreds of square kilometres at roughly the same horizon in a sedimentary sequence (Figure 28a). A near vertical crack filled with magma is known as a dyke (Figure 28b). Sills, dykes and lava flows, which can be radiometrically dated, are all used for bracketing the ages of sedimentary rocks in which they are found.

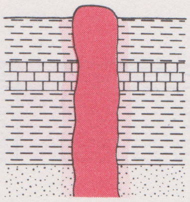
contact metamorphism

sill



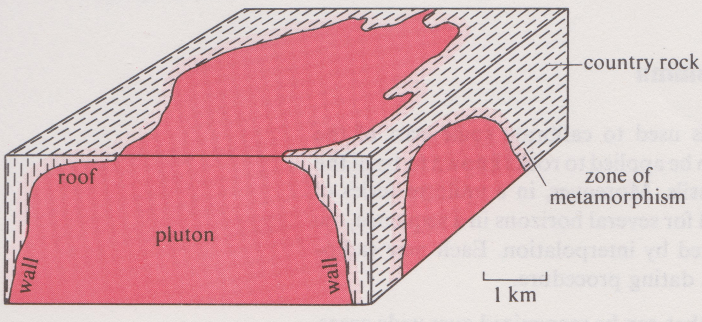
(a) sill

10 m



(b) dyke

10 m



(c) plutonic intrusion

FIGURE 28 Various types of igneous intrusions. (a) Cross-section of sill. The beds above and below are likely to have been baked (pale pink) by the intrusion (dark pink). (b) Cross-section of dyke. The rocks on both sides of the dyke may show the effects of baking by the intrusion. (c) Block diagram of a pluton. The zone of contact metamorphism around the igneous rock may be quite extensive.

In a similar way, large intrusions, which may represent many cubic kilometres of magma, and which have crystallized at a depth of several kilometres, can also be used to determine a minimum age for the surrounding rocks.

> Can you recall (from Units 6 and 7) what kind of rock usually occurs in these large *plutonic* intrusions (Figure 28c), and where, in plate-tectonic terms, they are often found?
>
> They are composed of granite, and commonly occur above *destructive* plate margins. (You will learn much more about destructive plate margins in Unit 27.)

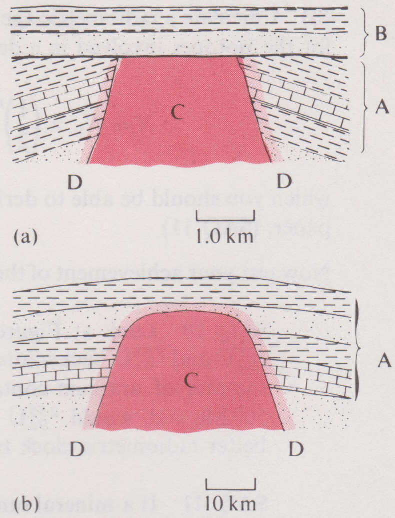


FIGURE 29 Diagrammatic sections through plutonic intrusions. (a) Plutonic rock, C, has intruded strata, A, forming a zone of contact metamorphism, D. After a period of uplift and erosion to expose the plutonic rock, a second series of sediments, B, were laid down, above the unconformity. Pebbles of rocks A, C and D may occur in beds B. Beds A are *older* than the igneous rock, C; beds B are *younger* than C. (b) Plutonic rock, C, has intruded beds A, and formed a zone of contact metamorphism, D. Here all the strata around the intrusion are all *older* than C and therefore there is a zone of contact metamorphism all around the intrusion.

The relationships seen in the field between an igneous intrusion and the surrounding sedimentary rocks are very important if the igneous rocks are to be used for dating purposes. For example, a granite may cut across the bedding of the adjacent strata and therefore be later than those strata (Figure 29b), or the contact between granite and sediments may be an unconformity, in which case the granite is older than the overlying sediments and does not metamorphose them at all (Figure 29a).

> **ITQ 20** Look at Figure 30, which shows in each case two sedimentary beds A and B and an igneous rock (shaded).
>
> (i) Which diagram(s) show(s) a lava?
>
> (ii) Which diagram(s) show(s) a sill?
>
> (iii) Which diagram(s) show(s) a dyke?
>
> (iv) In which diagram(s) will a radiometric age for the igneous rock give a *minimum* age for both A and B?
>
> (v) In which diagram(s) will a radiometric age for the igneous rock give a minimum age for A and a maximum for B?

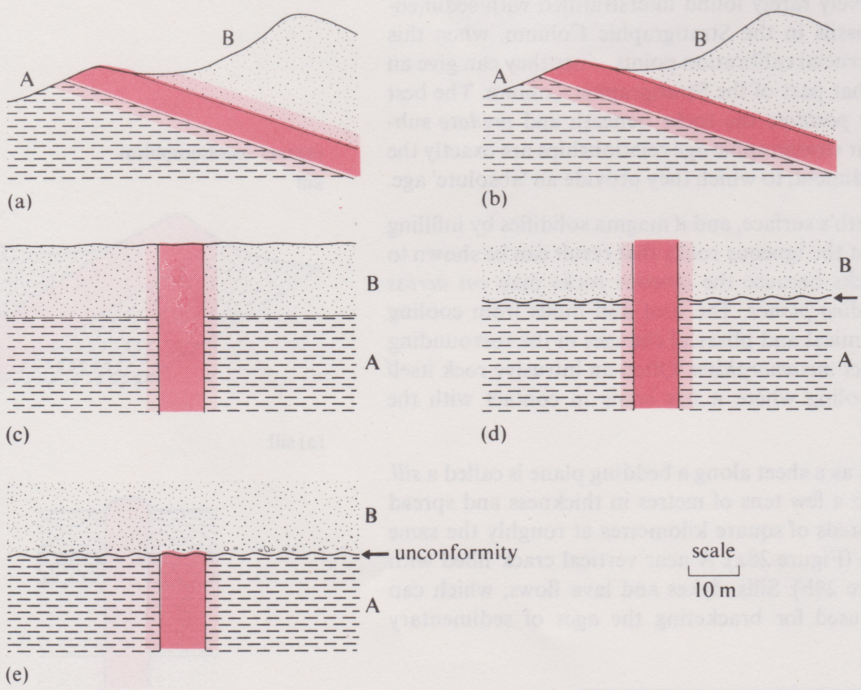


FIGURE 30 Diagrammatic sections through igneous rocks for use with ITQ 20. In each case there is an older (A) and younger (B) sedimentary rock and an igneous rock (dark pink). Metamorphosed sediments are shown in light pink.

6.2 Sub-division of the Stratigraphic Column

Each time a particular radiometric date is used to calibrate some part of the Stratigraphic Column, a similar age can then be applied to rocks known to be of the same age because they contain similar fossils. Moreover, in a uniform series of sediments, if radiometric ages can be found for several horizons in a sequence, the age range of rocks between can be estimated by interpolation. Each new radiometric date can then be used to refine this dating procedure.

Some unconformities, representing events that can be recognized over wide areas, can be dated quite precisely, and many of the geological Periods in the Stratigra-

phic Column are separated from the rocks above and below by such unconformities.

The use of the palaeomagnetic reversal timescale to establish the details of events of the past 4.5 Ma has already been discussed (Unit 5). The dates for this timescale again depend on the determination of real radiometric ages of some of the igneous rocks involved.

By the detailed correlation of these igneous dates from all parts of the world, virtually any horizon after the Precambrian in the Stratigraphic Column can now be allocated a 'date'. However, the individual zone, defined by fossils, remains the unit of calibration for the practising geologist in the field. Marker horizons, often characterized by one or more specific fossils, are used to establish the relative ages of individual outcrops. This is basically the same method used by William Smith nearly 200 years ago.

It is in the unravelling of Precambrian events, however, that radiometric dating has had the most impact. In the Precambrian there are abundant igneous and metamorphic rocks, which yield radiometric dates, but there is a far from complete sedimentary record. We now know that the Palaeozoic and more recent sediments, with their abundant fossils, represent little more than 10 per cent of the Earth's history, which stretches back to 4 600 Ma. We believe that processes similar to those we can now observe at the Earth's surface have been going on for more than two thousand million years, and we believe that the most recent episode of continental fragmentation and sea-floor spreading you studied in Units 6 and 7 is just the latest of many such episodes.

You will learn much more of the Earth's early history in Unit 28, where you will study topics concerned with the development of its internal structure, the evolution of its atmosphere, and the beginnings of life.

6.3 Objective of Section 6

Now that you have completed Section 6, you should be able to achieve the following additional Objective:

(a) To integrate given geological data, such as radiometric dates and the relationships of rocks to each other in the field, to work out relative and absolute ages. (SAQs 12 and 13)

Now test your achievement of this Objective by attempting the following SAQs.

SAQ 12 Look at Figure 31. There are two series of sedimentary rocks (A–E and F–H²) and two igneous intrusions, a dyke (J), and a sill (I).

(i) Which are the rocks of the older sedimentary series, and which the younger?

(ii) Is igneous rock I or J the older, and why?

(iii) Arrange the rocks in four age groups, starting with the oldest.

(iv) What is the surface at the base of rock F?

(v) If rock I were a lava flow, would that affect your answer to (iii)?

SAQ 13 (a) Is the granite in Figure 32a older or younger than the strata A–D? Give reasons for your answer.

(b) Is the granite in Figure 32b older or younger than the strata X–Z? Give reasons for your answer.

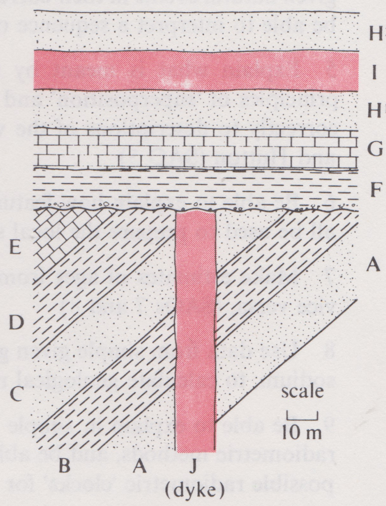
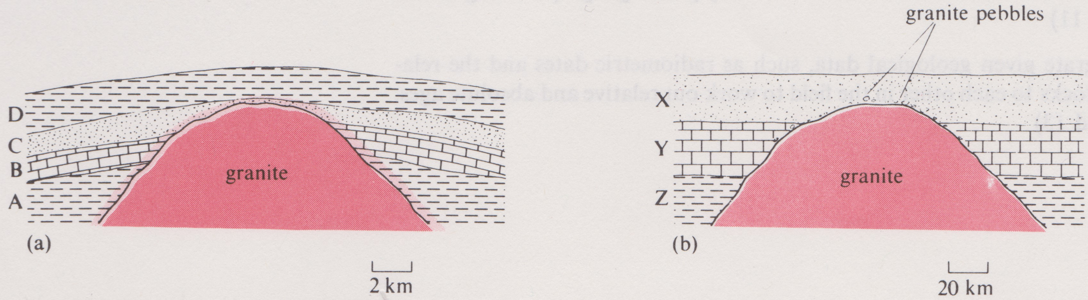


FIGURE 31 Cross-section of a quarry face (for use with SAQ 12).

FIGURE 32 Cross-section of granite intrusions (for use with SAQ 13).



Aims and Objectives

Apart from Objective 1, which relates to all the terms and concepts used in this Unit, the Objectives may be divided into two groups which are related to the Aims of this Unit as follows:

Aims

1 (*Objectives 3, 4, 5, 6, and 11*) To describe the Stratigraphic Column as a record of the Earth's history, and to explain the principles of relative dating used to construct this Column.

2 (*Objectives 2, 7, 8, 9, 10 and 11*) To describe the various methods of absolute dating which can be used to give an exact chronology for the Earth's past, particularly radioactive methods.

Objectives

1 Define correctly, recognize the best definitions of, and distinguish between true and false statements concerning the terms, concepts and principles listed in Table A.

2 Perform simple calculations involving time over many orders of magnitude. (SAQ 1)

3 Define the terms Era and Period, recall the four major Eras of geological time, and from given data on the Stratigraphic Column assign a rock of given age to its correct Period. (SAQ 2)

4 Be able to apply the principle that the present is the key to the past, by placing given natural events in their correct chronological order. For example, you should be able to interpret a sequence of varved sediments. (SAQs 3 and 4)

5 Explain what is meant by the terms 'catastrophism', 'uniformitarianism', principles of 'superposition' and 'faunal succession' and be able to apply these correctly to descriptions of the work of early geologists such as Cuvier, Smith and Hutton (SAQ 5)

6 Be able to explain how features such as fossils, rock types, and age dates can all be used to prepare the local stratigraphic column for an area. (SAQ 6)

7 Make estimates of ages from given rates of simple geological processes and vice versa. (SAQs 7 and 8)

8 Use data from simple given geological or geochemical cycles, such as that for sodium, to calculate geological rates and dates. (SAQ 9)

9 Be able to explain in simple terms how geological materials can be dated by radiometric methods, and be able to choose the most appropriate from several possible radiometric 'clocks' for a given dating problem. (SAQ 10)

10 Calculate a radiometric age from a given half-life and parent : daughter ratio for the isotopes involved in the decay scheme, using the decay equation

$$N = N_0 \times \left(\frac{1}{2}\right)^n \quad \text{or} \quad \frac{t}{\tau} = \log\left(\frac{N}{N_0}\right) \Big/ \log\left(\frac{1}{2}\right)$$

which you should be able to derive or recall, or by plotting a graph on log–linear paper. (SAQ 11)

11 To integrate given geological data, such as radiometric dates and the relationships of rocks to each other in the field to work out relative and absolute ages. (SAQs 12 and 13)

Further reading

Gass, I. G., Smith, P. J. and Wilson, R. C. L. (eds.) (1972) *Understanding the Earth*, 2nd edn., Artemis Press. Chapter 2, Measuring Geological Time, by S. Moorbath; Chapter 13, Looking back through Time, by E. K. Walton.

Eicher, D. L. (1976) *Geologic Time*, 2nd edn., Prentice-Hall.

Acknowledgements

Grateful acknowledgement is made to the following sources for material used in this Unit:

Cover Detailed E–W Section, Northern Granite, Isle of Arran, Strathclyde, after watercolour from G. Y. Craig (ed.) (1978) *James Hutton's Theory of the Earth: The Lost Drawings*, Scottish Academic Press; *Figures 1 and 23* based on D. L. Eicher (1976) *Geologic Time*, Prentice-Hall; *Figure 2* based on data from Chas. B. Hunt (1959) 'Dating of mining camps with tin cans and bottles', *GeoTimes*, III, 8; *Figure 7* Hale Observatories; *Figure 8* NASA; *Figure 18* Radio Times Hulton Picture Library, from a block in possession of the Edinburgh Geological Society; *Figure 19a* G. C. Brown; *Figure 19b* I. G. Gass; *Figure 20* Institute of Geological Sciences.

ITQ answers and comments

ITQ 1 (a) Igneous: S1, S2, S3, S4, S5. All show typical crystalline, even-grained, compact, igneous texture, with no sign of any bedding or metamorphic banding. The vesicular basalt (S2) has many 'frozen' gas bubbles.

(b) Sedimentary: S6, S7. S6 shows typical cemented sandy texture, while S7, a limestone, is composed largely of broken organic remains of *calcite* ($CaCO_3$) material, i.e. it is full of fossil shell fragments.

(c) Metamorphic: S8, S9, S10. All show *crystalline* texture rather than the fragmental texture typical of sediments, and also all show 'banding' typically developed on some scale in most metamorphic rocks.

ITQ 2 (a) S2, the basalt from Auvergne, because it contains by far the highest porosity. It has air spaces due to the gas bubbles trapped in this vesicular lava.

(b) S4, the peridotite, because it is made of very dense minerals. You will learn in Unit 27 why olivine, the chief mineral in the peridotite, is the densest of all the common silicate minerals. At this stage you should have realized that since all igneous rocks except S2 have essentially no porosity, differences in rock density *must* be due to differences in the density of the minerals they contain.

(c) This is difficult to answer at this stage, but you may have deduced that these two rocks are probably of about the same density because both contain essentially no porosity and are made of the same minerals, quartz, feldspar and some mica. (You will learn more about these minerals in Unit 27.)

ITQ 3 (a) 70 years × 365 days × 24 hours × 60 minutes × 60 seconds

or

$(7 \times 10^1) \times (3.65 \times 10^2) \times (2.4 \times 10^1) \times (6 \times 10^1) \times (6 \times 10^1)$

$$= 2\,207 \times 10^6\,\text{s}$$

$$2.2 \times 10^9\,\text{s}$$

(b) The age of the ocean basins is

$$\frac{100}{70} \times 10^6 \text{ lifespans}$$

$$= \frac{10}{7} \times 10^6 \text{ lifespans}$$

$$\approx 1.4 \times 10^6 \text{ lifespans}$$

(c) If the age of Earth is 4 600 million years, then

$$= \frac{4.6 \times 10^8}{7} \text{ lifespans}$$

$$\approx 6.6 \times 10^7 \text{ lifespans}$$

ITQ 4 Column A is pre-1900: it contains square headed nails (6), hand finished necks for corks (3), and soldered tin cans (1); all of these are pre-1900 materials. Column B is 1900–1920; it contains items 4, 7 and 1. Column C is 1920–1930; it contains 2, 7 and 5.

ITQ 5 A, D, B, E, C.

A, D, B are all stone axes. A is the crudest and the most primitive, and, therefore, the oldest; D is more carefully fashioned; and B later still, being set in a handle; E, the bronze axe, comes next, before C, the iron one.

ITQ 6 The lighter material in the centre of the photograph is more densely cratered and must have been exposed to meteorite bombardment for a longer time; it is therefore the older area. The darker material below is much less heavily cratered, and contains few craters that are more than 1 mm in diameter on this photograph.

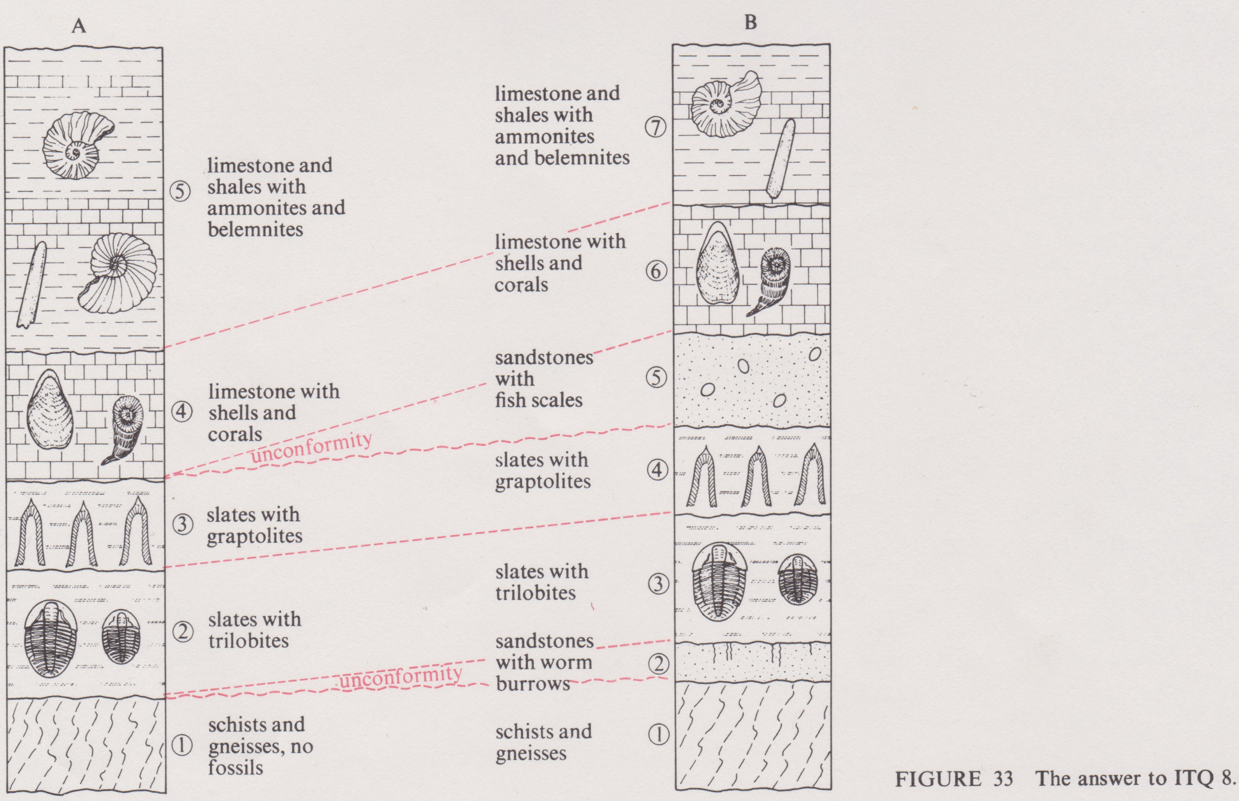


FIGURE 33 The answer to ITQ 8.

ITQ 7 The unconformity represents about 60 Ma, that is, from the end of the Cretaceous until the appearance of man at about the beginning of the Quaternary Period (see Figure 1).

ITQ 8 (a) The beds are correlated simply by matching similar fossils: A1 = B1; A2 = B3; A3 = B4; A4 = B6; A5 = B7. See Figure 33.

(b) An unconformity in column A between beds 1 and 2 is represented by a sandstone (dotted) bed in column B between beds 1 and 3. Similarly, another unconformity between A3 and A4 is represented by another sandstone between B4 and B6. (See Figure 33). It is likely, therefore, that area A was above sea-level and suffered erosion twice while sandstones were deposited at B.

ITQ 9 From the Tertiary back to the top of the Lower Palaeozoic, that is, about the last 400 Ma. From the London Clay (Eocene) at 50 Ma back to Smith's red and dunstone (Devonian) at 400 Ma. (The 'killas and slates' at the bottom of Smith's column are the Silurian and strata below in the modern Column, but that is difficult to decide from Figures 16 and 17.)

ITQ 10

(a) Area of delta deposits $= (3.4 \times 10^{10}) + (1.6 \times 10^{10})\,\text{m}^2$

$= 5 \times 10^{10}\,\text{m}^2$

Depth $= 1.6 \times 10^2\,\text{m}$

Volume $=$ area $\times$ depth

$= 5 \times 10^{10} \times 1.6 \times 10^2\,\text{m}^3$

$= 8 \times 10^{12}\,\text{m}^3$

Annual volume of sediments $= 1.11 \times 10^8\,\text{m}^3\,\text{yr}^{-1}$

$$\text{Age of delta} = \frac{\text{volume of delta}}{\text{annual volume of sediments}}$$

$$= \frac{8 \times 10^{12}\,\text{m}^3}{1.11 \times 10^8\,\text{m}^3\,\text{yr}^{-1}}$$

$$= 7.2 \times 10^4\ \text{years}$$

$$\approx 70\,000\ \text{years}$$

So the age of the delta is likely to be at least 70 000 years. In fact, allowing for the squeezing down of older sediments by later deposits, the delta could be well over 100 000 years old.

$$\text{(b) Annual rate of accumulation} = \frac{\text{annual volume of sediments}}{\text{area of delta}}$$

$$= \frac{1.11 \times 10^8\,\text{m}^3\,\text{yr}^{-1}}{5 \times 10^{10}\,\text{m}^2}$$

$$\approx 0.22 \times 10^{-2}\,\text{m}\,\text{yr}^{-1}$$

$$\approx 2.2\,\text{mm}\,\text{yr}^{-1}$$

ITQ 11 If 0.6 m accumulates in 1 000 years, 50 000 m will have accumulated in

$$\frac{1\,000 \times 50\,000}{0.6}\ \text{years}$$

$$= \frac{10^3 \times 5 \times 10^4}{6 \times 10^{-1}}\ \text{years}$$

$$= 0.83 \times 10^8\ \text{years}$$

$$\approx 80\ \text{Ma}$$

ITQ 12 Joly's calculation of the age of the oceans
= total salt in the ocean/annual input of salt by rivers

But if the input of '*new*' salt is *less* than that brought down by rivers because of salt recycled by sea-spray, we should have:

Age of the oceans = total salt in the oceans/annual input of salt by rivers *minus* salt recycled by spray

The age calculated from the first equation will clearly be less than that from the second. Neglecting the effect of sea-spray would therefore lead to an *under-estimate* of the age.

ITQ 13 Using a similar calculation to that in the answer to ITQ 12,

age = total sodium in ocean/annual input of 'new' sodium

we have $\dfrac{15 \times 10^{15}\ \text{tonnes}}{6 \times 10^7\ \text{tonnes}\,\text{yr}^{-1}}$

$= 2.5 \times 10^8\,\text{yr}$

$= 250\,\text{Ma}$

ITQ 14 Because virtually all the activity of $^{14}_{6}C$ is lost long before 1 Ma. In fact, useful dating is confined to the last 60 000 years. We need an isotope of half-life comparable in length to the geological time being measured.

ITQ 15 Number of half-lives from noon until 1800 hours = 6, therefore the number of parent atoms remaining can be calculated for the first 6 hours as in Table 7.

Number of parent atoms left at 1800 hours $= \dfrac{10^{10}}{64}$ $= \dfrac{1 \times 10^{1}}{0{\cdot}64 \times 10^{2}}$

$= 1.56 \times \cancel{10^8}$ atoms 10^9

Note An alternative way of working out the number of atoms remaining after six half-lives is by using equation 1:

$$N = N_0 \times (\tfrac{1}{2})^n \qquad (1)^*$$

Therefore $N = 10^{10} \times (\tfrac{1}{2})^6$

$$= 10^{10} \times \frac{1}{64}$$

$= 1.56 \times \cancel{10^8}$ atoms 10^9

TABLE 7 (For ITQ 15)

Time	1200 (noon)	1300	1400	1500	1600	1700	1800
Half-lives	0	1	2	3	4	5	6
Number of parent atoms left	10^{10}	$10^{10} \times \frac{1}{2}$	$10^{10} \times \frac{1}{4}$	$10^{10} \times \frac{1}{8}$	$10^{10} \times \frac{1}{16}$	$10^{10} \times \frac{1}{32}$	$10^{10} \times \frac{1}{64}$

ITQ 16 (See Figure 34). After 1 hour 50 per cent of parent isotope remains; after 2 hours 25 per cent of parent isotope remains; after 3 hours $12\frac{1}{2}$ per cent of parent isotope remains.

(a) 1 : 500 ratio (0.2 per cent of parent isotope left) will be reached in 9 half-lives = 9 hours. Compare this with the answer obtained by calculation on p. 35, which gave 8.97 hours.

(b) 1 : 5 000 ratio (0.02 per cent) will be reached in about 12.3 half-lives $\approx$ 12.3 hours.

ITQ 17 (a) If the proportions of parent : daughter are 1 : 1 then the sample is exactly one half-life old, that is, 704 Ma.

(b) If the parent : daughter ratio is 1 : 15, the rock is exactly 4 half-lives old since only 1/16 of the parent nucleii survive (the other 15/16 being converted into daughter nuclei—see Table 7 in the answer to ITQ 15), so the age must be 4 × 704 = 2 816 Ma.

or, by using $\frac{t}{\tau} = \log\left(\frac{N}{N_0}\right) \Big/ \log\left(\frac{1}{2}\right)$ (3)*

$$t = 704 \log\left(\frac{1}{16}\right) \Big/ \log\left(\frac{1}{2}\right) \text{Ma}$$

Using your calculator, *key*;

$$704,\ \times,\ 16,\ \frac{1}{x},\ \log,\ \div,\ 2,\ \frac{1}{x},\ \log,\ =2\,816$$

Therefore $t = 2\,816$ Ma.

ITQ 18 (a) Maximum age of the Earth from isotopic proportions of $^{238}_{92}U$ and $^{206}_{82}Pb$:

You are told that the half-life, τ, = 4 467 Ma.

N, parent $^{238}_{92}U$, = 10.0

$(N_0 - N)$, daughter $^{206}_{82}Pb$, = 18.5

Therefore N_0, original parent $^{238}_{92}U$ value, = 28.5

(i) *By calculation*

You know that $\frac{t}{\tau} = \log\left(\frac{N}{N_0}\right) \Big/ \log\left(\frac{1}{2}\right)$ (3)*

Therefore $t = 4\,467 \times \log\left(\frac{10}{28.5}\right) \Big/ \log\left(\frac{1}{2}\right)$ Ma

$= 4\,467 \times \log\left(\frac{1}{2.85}\right) \Big/ \log\left(\frac{1}{2}\right)$ Ma

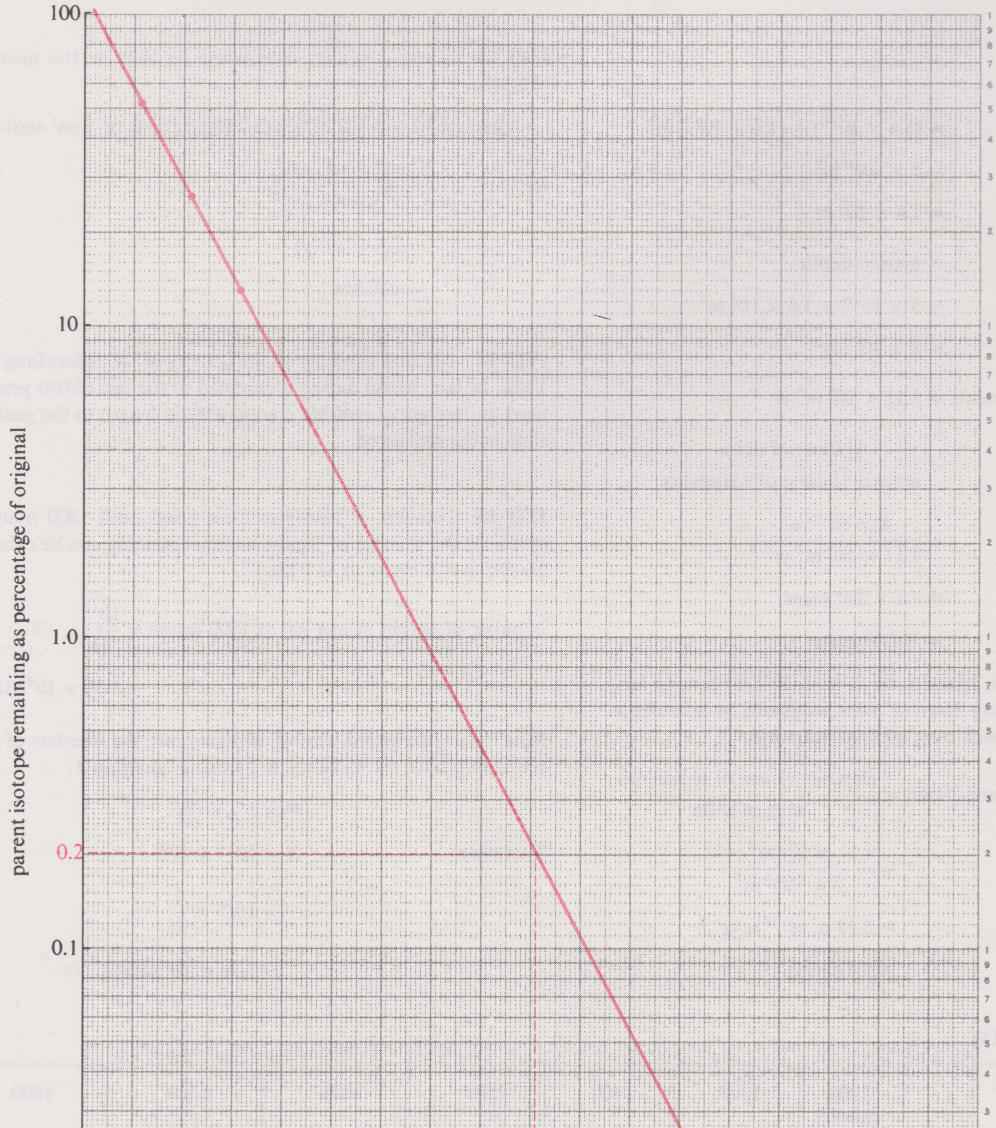


FIGURE 34 The answer to ITQ 16.

Using your calculator, *key*:

$$4\,467\ ,\ \times\ ,\ 2.85\ ,\ \frac{1}{x}\ ,\ \log\ ,\ \div\ ,\ 2\ ,\ \frac{1}{x}\ ,\ \log\ ,\ =\ 6\,749$$

Therefore $t = 6\,749$ Ma.

(ii) *Graphically*, using Figure 27 (see Figure 35).

Plot present-day value $^{238}_{92}U$, which is 10.0.

Since the half-life for this decay process is 4 467 Ma, there must have been twice as much $^{238}_{92}U$, i.e. 20 units, at 4 467 Ma ago: plot this point on the graph. Connect these two points with a straight line (cf. Figure 24). This represents the amount of $^{238}_{92}U$ present at any time in the past, that is, it is the uranium decay curve. Going back along this line is equivalent to 'converting' the $^{206}_{82}Pb$ daughter back to its parent $^{238}_{92}U$. Eventually a point is reached where all the 18.5 units of lead have been 'converted' back to uranium and this is the maximum age at which the process could have started. This point is at 28.5 units, which is equivalent to 6 750 Ma ago.

(b) $$N = 0.072\,5$$

$$(N_0 - N) = 15.6$$

Therefore $N_0 = 15.672\,5$

(i) *By calculation*

$$\frac{t}{\tau} = \log\left(\frac{N}{N_0}\right) \Big/ \log\left(\frac{1}{2}\right) \qquad (3)^*$$

Therefore $$t = 704 \times \log\left(\frac{0.0725}{15.6725}\right) \Big/ \log\left(\frac{1}{2}\right) \text{ Ma}$$

Since N/N_0 is not a simple fraction, you should start the calculation here. Using your calculator, *key*:

$$0.0725\ ,\ \div\ ,\ 15.6725\ ,\ =\ ,\ \log\ ,\ \times\ ,\ 704,\ \div\ ,\ 2\ ,\ \frac{1}{x}\ ,\ \log\ ,\ =\ 5\,460$$

Therefore $t = 5\,460$ Ma.

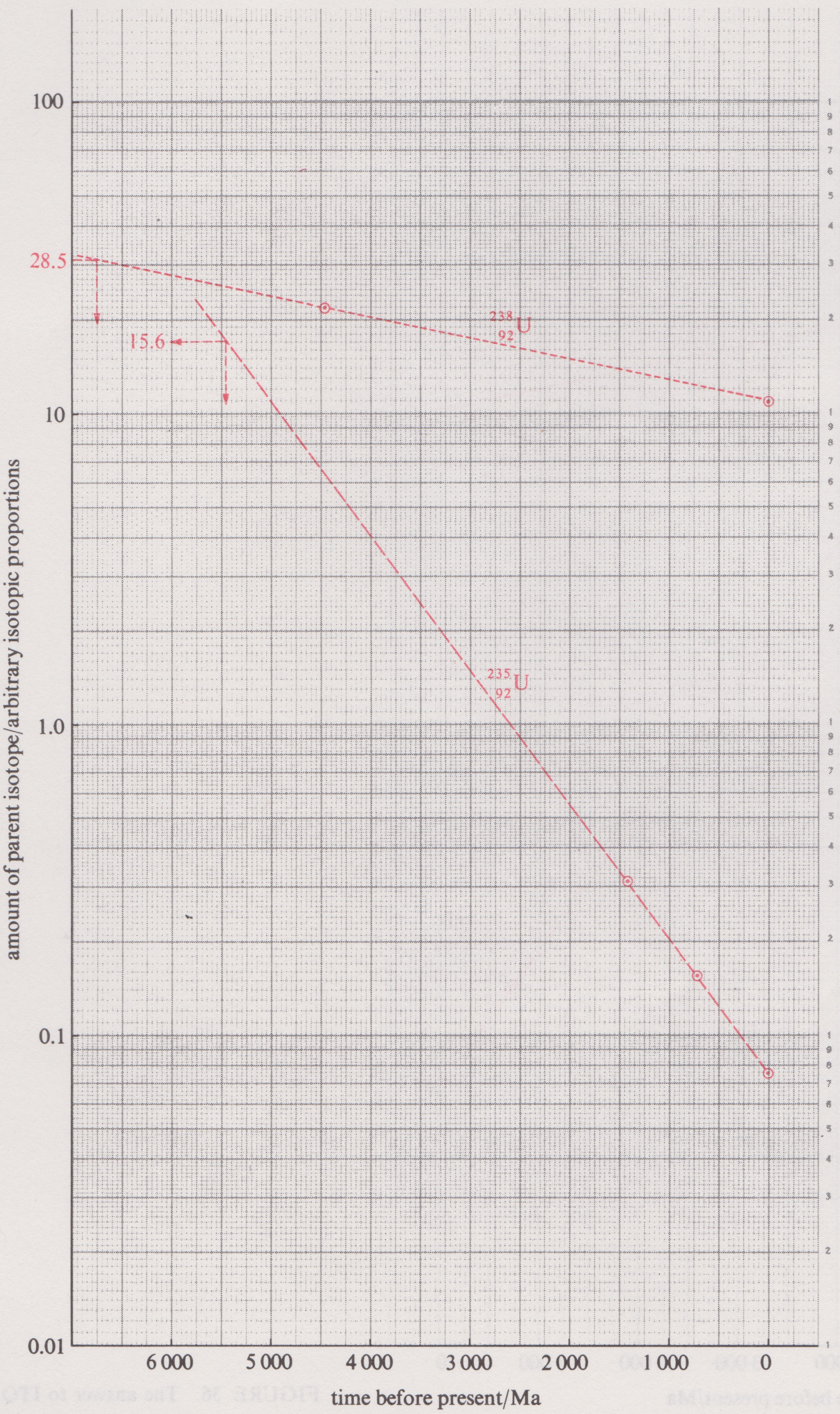


FIGURE 35 The answer to ITQ 18.

(ii) *Graphically*, using Figure 27 (see Figure 35).

Using the same method as you did in (a) (ii), it is easy to plot the rate at which $^{238}_{92}U$ increases back in time. Two half-lives are plotted on Figure 35. From this you can see that all present daughter $^{207}_{82}Pb$ 'converts' back to $^{235}_{92}U$ approx. 5 450 Ma ago.

ITQ 19 (a) 'Real' age of the Earth from isotopic proportions of $^{238}_{92}U$ and $^{206}_{82}Pb$, allowing for 'primordial lead' of meteorites.

$$N\text{, parent } ^{238}_{92}U = 10.0$$

$$(N_0 - N)\text{, daughter } ^{206}_{82}Pb = (18.5 - 8.0) = 10.5$$

Therefore N_0, original parent $^{238}_{92}U$ value = 20.5

(i) *By calculation*

You know that $\dfrac{t}{\tau} = \log\left(\dfrac{N}{N_0}\right) \Big/ \log\left(\dfrac{1}{2}\right)$ (3)*

Therefore $t = 4\,467 \log\left(\dfrac{10}{20.5}\right) \Big/ \log\left(\dfrac{1}{2}\right)$ Ma

$= 4\,467 \log\left(\dfrac{1}{2.05}\right) \Big/ \log\left(\dfrac{1}{2}\right)$ Ma

Using your calculator, *key*:

$$4\,467, \times, 2.05, \frac{1}{x}, \log, \div, 2, \frac{1}{x}, \log, = 4\,626$$

Therefore $t = 4\,626$ Ma.

(ii) *Graphically*, using Figure 27 (see Figure 36).

Read off from the $^{238}_{92}U$ line the value corresponding to the new value of N_0, that is, 20.5.

$$t \approx 4\,600 \text{ Ma.}$$

(b) 'Real' age of the Earth from isotopic proportion of $^{235}_{92}U$ and $^{207}_{82}Pb$, allowing for 'primordial lead' of meteorites.

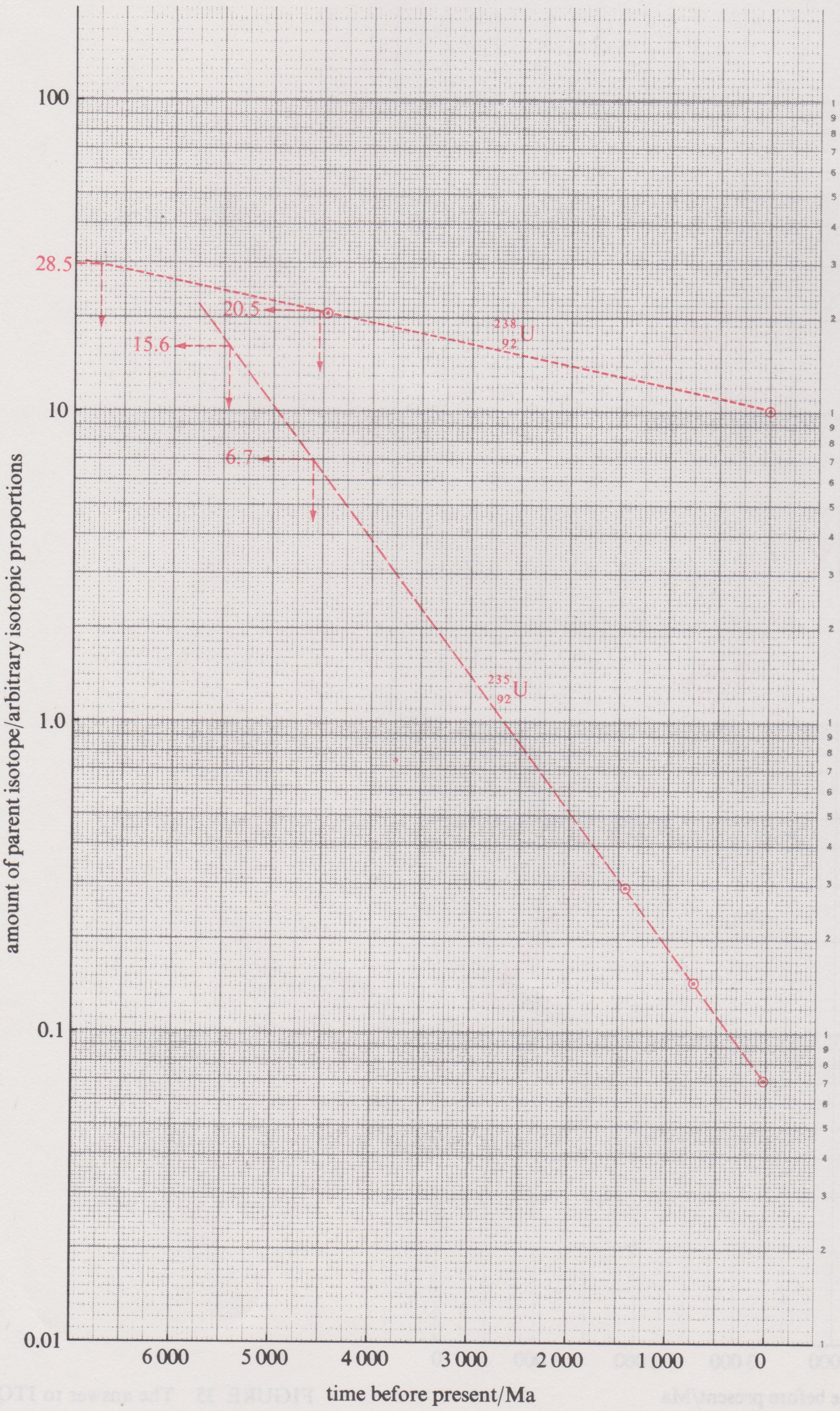


FIGURE 36 The answer to ITQ 19.

$$N = 0.0725$$

$$(N_0 - N) = (15.6 - 9.0) = 6.6$$

Therefore $N_0 = 6.6725$

(i) *By calculation*

$$\frac{t}{\tau} = \log\left(\frac{N}{N_0}\right) \Big/ \log\left(\frac{1}{2}\right)$$

Therefore $t = 704 \times \log\left(\frac{0.0725}{6.6725}\right) \Big/ \log\left(\frac{1}{2}\right)$ Ma

Using your calculator, *key*:

$$0.0725, \div, 6.6725, =, \log, \times, 704, \div, 2, \frac{1}{x}, \log, = 4593$$

Therefore $t = 4\,593$ Ma.

(ii) *Graphically*, using Figure 27 (see Figure 36).

Read off the value corresponding to the new value of N_0, namely about 6.7.

$$t \approx 4\,600 \text{ Ma.}$$

ITQ 20 (i) (b). There is only one baked contact.

(ii) (a). There are two baked contacts

(3)* (iii) (c), (d) and (e).

(iv) (a), (c) and (d). In (a) the igneous rock metamorphoses the top of A and the bottom of B. Therefore they must be *older* than the sill. In (c) and (d) the dyke cuts and metamorphoses both A and B and must therefore be *younger* than A and B.

(v) (b) and (e). In (b) sedimentary rock B was laid down on the lava. It must therefore be *younger* than the lava. The baked zone at the top of A shows that the lava is *younger* than A. In (e) the dyke is *younger* than A because it cuts and metamorphoses it. It is *older* than B because erosion occurred after the dyke was intruded and before B was laid down. (Cf. Figure 29a.)

SAQ answers and comments

SAQ 1 (a) If 4 600 Ma are equivalent to 3 hours then 1 Ma is equivalent to $3/4.6 \times 10^3$ hours and 3 Ma are equivalent to $3 \times 3/4.6 \times 10^3$ hours or $3 \times 3 \times 3\,600/4.6 \times 10^3$ seconds ≈ 7 seconds.

Man would thus appear about 7 seconds before the end of the film; a couple of sneezes and you could miss him!

(b) If 3 Ma is equivalent to 7 seconds then 1 year is equivalent to $7/3 \times 10^6$ seconds and 5×10^3 years are equivalent to $7 \times 5 \times 10^3/3 \times 10^6$ seconds $\approx 1.2 \times 10^{-2}$ seconds.

So civilization would appear about a hundredth of a second from the end; it might just get on the very last frame of the film!

SAQ 2 (a) S1, S5, S6, S7, S8, S9 are Palaeozoic; S4 and S10 are Mesozoic; S2 and S3 are Cenozoic.

(b) S1 Devonian; S2 Tertiary; S3 Tertiary; S4 Cretaceous; S5 Silurian/Ordovician; S6 Carboniferous; S7 Carboniferous; S8 Silurian; S9 Ordovician; S10 Cretaceous.

SAQ 3 Graded bedding, with coarser sediment at the bottom of each unit gradually becoming finer grained towards the top, is interpreted as representing the gradual transition from rapid deposition of coarse sediment during the summer, to deposition of the finer suspended clay particles during the winter, when no sediment was coming into the lake.

SAQ 4 (i) See Figure 37. (The correlation lines between distinctive marker horizons are shown in red.)

(ii) See Figure 37. (The stratigraphic column for these beds is made by 'stacking' up all the beds in chronological order, oldest at the bottom.)

(iii) The oldest beds are at the bottom of column E.

Note Bed b.c. easily correlates across columns B, C and D. The pair of thick beds at the top of E correlate with those at the bottom of C. The beds at the top of B correlate with those at the bottom of A.

(iv) 158 years, as shown in the stratigraphic column on the right-hand side of Figure 37.

SAQ 5 Neither. Smith applied the faunal succession as a way of correlating rock strata to help him make a geological map. It is possible to interpret the faunal succession in *either* a catastrophist way (Cuvier) or in a uniformitarianist way (Darwin).

SAQ 6 If there is only one type of rock present, it would be difficult to use rock-stratigraphic units or beds. You would, therefore, divide the column into biostratigraphic units, or *zones*, by the fossils.

SAQ 7 (a) Lyell's data were: $1.11 \times 10^8\,\text{m}^3\,\text{yr}^{-1}$.

$$1\,\text{m}^3 \text{ weighs } 2.2\,\text{tonnes}$$

$$1.11 \times 10^8\,\text{m}^3 \text{ weighs } 2.2 \times 1.11 \times 10^8 \text{ tonnes}$$

$$= 2.44 \times 10^8\,\text{tonnes yr}^{-1}$$

Modern estimates are

$$550 \text{ million tonnes yr}^{-1}$$

$$= 5.50 \times 10^8\,\text{tonnes yr}^{-1}$$

Lyell's estimate of 2.42×10^8 tonnes yr^{-1} is approximately 44 per cent of the modern estimate.

(b) Lyell would have calculated a younger age for the delta. Since his estimates of annual influx of sediment were about half the modern figure, his calculation of the age would have been also reduced by a half, i.e. to $\approx 30\,000$ years.

SAQ 8 (a)

$$2.2\,\text{mm yr}^{-1} = 2.2 \times 10^{-3}\,\text{m yr}^{-1}$$

2.2×10^{-3} metres accumulate in 1 year

$$50\,000 \text{ metres accumulate in } \frac{50\,000}{2.2 \times 10^{-3}} \text{ years}$$

$$= \frac{5 \times 10^4}{2.2 \times 10^{-3}} \text{ years}$$

$$\approx 2.3 \times 10^7 \text{ years}$$

$$\approx 23\,\text{Ma}$$

(b) Because the rate of sedimentation is very fast in deltaic environments compared with almost all other sedimentary environments, most of the strata in the stratigraphic column will have accumulated at a much slower rate, and so represent a larger time-span. Also, sedimentary rocks tend to be thinner than the beds of loose sediment from which they are formed as the weight of overlying strata squeezes out excess water.

SAQ 9 (a) Joly's calculation was based on the assumption that all salt brought into the oceans is 'new' salt; if some of it is salt recycled by spray, the calculation will over-estimate the salt added annually to the oceans by rivers, and so *under-estimate* the age of the ocean.

(b) Plate tectonics helps sodium from the oceans to be recycled to crustal rocks, since any salt (for example, that in pore spaces in oceanic crustal rocks) carried into a Benioff zone will be recycled as igneous or metamorphic rocks. You will learn more about this in Unit 27.

SAQ 10 ${}^{235}_{92}\text{U} \longrightarrow {}^{207}_{82}\text{Pb}$, with its faster decay rate. Between 500 Ma ago and the present there has been considerable change in the proportion of ${}^{235}_{92}\text{U}$ to ${}^{207}_{82}\text{Pb}$. With its slower decay rate ${}^{238}_{92}\text{U}$ has decayed less in the last 500 Ma, so it should provide less reliable dates.

SAQ 11 Again, there are two ways of working this out.

(i) *By calculation.*

Daughter : parent ratio = 20; $N = 1$ and $N_0 = 21$.

$$\tau = 704\,\text{Ma}$$

$$\frac{t}{\tau} = \log\left(\frac{N}{N_0}\right) \Big/ \log\left(\frac{1}{2}\right) \qquad (3)^*$$

Therefore $$t = 704 \log\left(\frac{1}{21}\right) \Big/ \log\left(\frac{1}{2}\right) \text{ Ma}$$

Using your calculator, *key:*

$$704\,,\ \times\,,\ 21\,,\ \frac{1}{x}\,,\ \log\,,\ \div\,,\ 2\,,\ \frac{1}{x}\,,\ \log\ =\ 3\,092$$

Therefore $t = 3\,092$ Ma.

(ii) *Graphically*, using Figure 24. (See Figure 34, answer to ITQ 16.)

The parent : daughter ratio is 1 : 20, therefore only 5 per cent of the original parent is left. This will happen after about 4.4 half-lives (from Figure 34).

$$t \approx 4.4 \times 704$$

$$t \approx 3\,100\,\text{Ma}$$

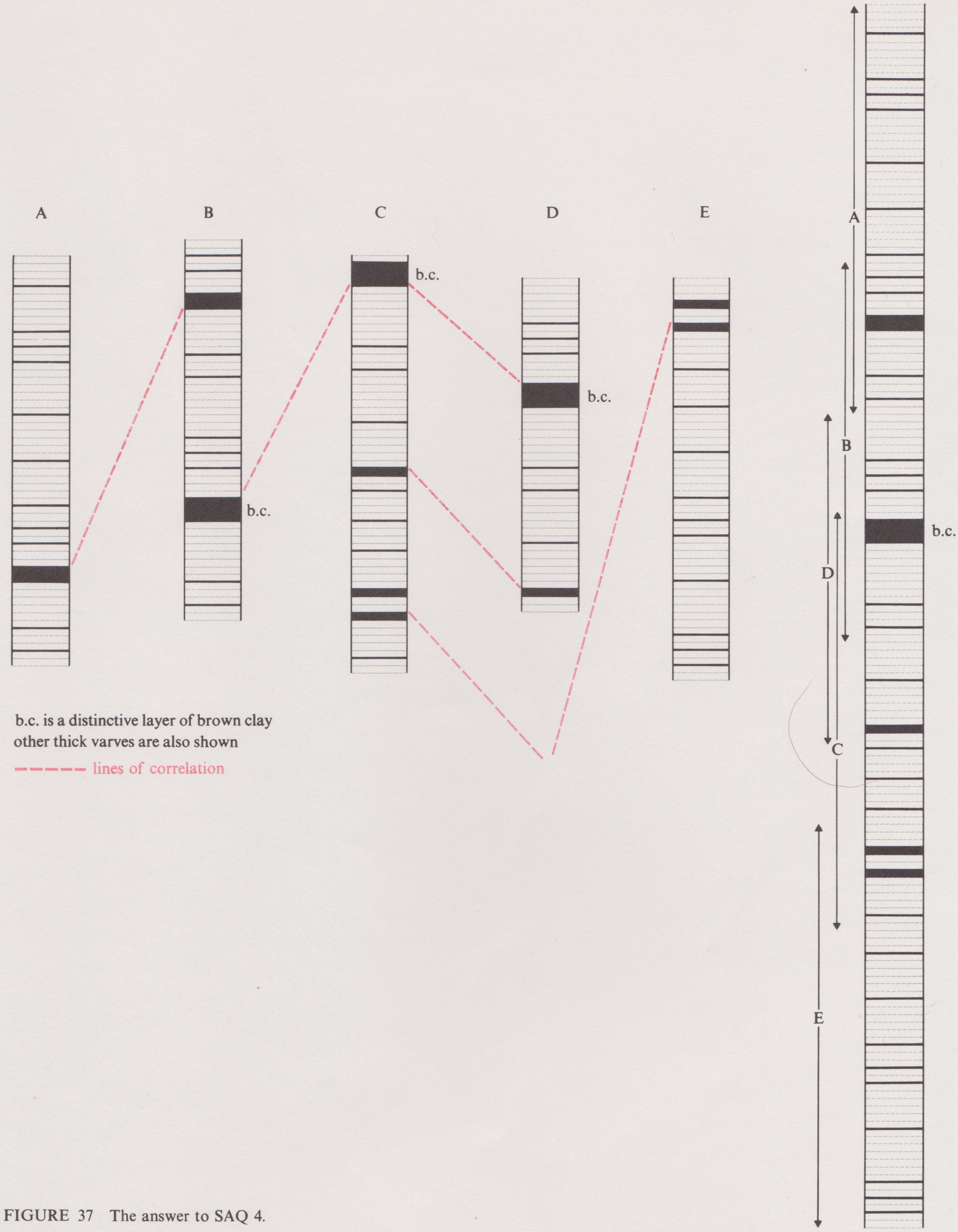


FIGURE 37 The answer to SAQ 4.

SAQ 12 (i) A–E are the older sedimentary series, below the unconformity at the base of F. F–H^2 are the younger series above the unconformity.

(ii) J is the older, because it was eroded before the second sedimentary series was laid down.

(iii) The sequence is: A–E, the first sedimentary series; intrusion of dyke, J; F–H^2, the second sedimentary series; intrusion of sill, I.

(iv) An unconformity or old erosion surface.

(v) Yes. If rock I were a lava flow, not a sill, then it would represent a break in sedimentation between H^1 and H^2, and so be *older* than H^2.

SAQ 13 (a) Younger. The granite cuts across the strata A–D, and these sediments have all been metamorphosed where they come in contact with the granite.

(b) Older. There is no evidence of metamorphism and there are pebbles of granite in the overlying sediments. The upper surface of the granite is a major unconformity. The granite must originally have been intruded into crustal rocks. Erosion removed these rocks and cut into the granite, to leave a huge granite hill. Sediments Z and Y accumulated against the sides, and finally X completely covered the granite.

0 335 08065 0
The Open University Press